AD 741786

AD

HDL-TR-1588

ORGANIC ELECTROLYTE BATTERY SYSTEMS

by

Jeffrey T. Nelson

Carla F. Green

March 1972

DDC
RECEIVED
MAY 15 1972
B

U.S. ARMY MATERIEL COMMAND

HARRY DIAMOND LABORATORIES

WASHINGTON, D.C. 20438

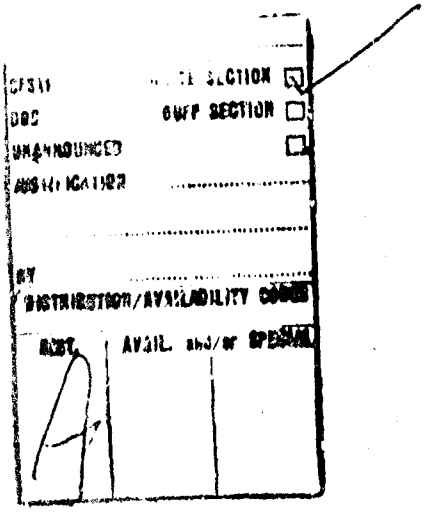
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

108

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturers' or trade names does not constitute an official indorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.



UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Harry Diamond Laboratories Washington, D.C. 20438	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

ORGANIC ELECTROLYTE BATTERY SYSTEMS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Jeffrey T. Nelson, Carla F. Green

6. REPORT DATE March 1972	7a. TOTAL NO OF PAGES 116	7b. NO OF REFS 101
8a. CONTRACT OR GRANT NO. b. PROJECT NO. DA-1T061102A34A c. AMCMS Code: 501B.11.86000 HDL Proj: 9EC94 d.	9a. ORIGINATOR'S REPORT NUMBER(S) HDL-TR-1588 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY USAMC

13. ABSTRACT

A search of the pertinent literature on organic electrolyte battery systems has been conducted to determine which systems, if any, might be useful to fuze power supplies. The data found in the literature, evaluated in the light of the requirements necessary for such power supplies, were found to be not specifically applicable, but useful only in a qualitative sense in providing guidance for studies at HDL. A plan of study and a list of three anodes, eight solvents, seven solutes, and seven cathodes derived from these data are presented.

DD FORM 1 NOV 68 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Organic Electrolyte						
Non-Aqueous Electrolyte						
Electrode Couples						
Anodes						
Cathodes						
Electrolytic Solutions						
Solvents						
Solutes						

AD

DA-1T061102A34A
AMCMS Code: 501B.11.86000
HDL Proj: 9EC94

HDL-TR-1588

ORGANIC ELECTROLYTE BATTERY SYSTEMS

by

Jeffrey T. Nelson

Carla F. Green

March 1972

US ARMY MATERIEL COMMAND
HARRY DIAMOND LABORATORIES
WASHINGTON DC 20438

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

ABSTRACT

A search of the pertinent literature on organic electrolyte battery systems has been conducted to determine which systems, if any, might be useful as fuze power supplies. The data in the literature, evaluated in the light of the requirements necessary for such power supplies, were found to be not specifically applicable, but useful only in a qualitative sense in providing guidance for studies at HDL. A plan of study and a list of three anodes, eight solvents, seven solutes, and seven cathodes derived from these data are presented.

CONTENTS

APPENDICES

Preceding page blank

1. INTRODUCTION

The storage and low temperature requirements for fuze power supplies have severely limited the number of electrochemical systems that can be used for these applications. Fuze power supplies must activate and operate at -40°F after 10 to 20 years storage at -65°F to +160°F. At present, the only liquid electrolyte enjoying widespread use in fuze power supplies is the fluoboric acid system. However, the performance capabilities of this system are limited by corrosion and adhesion problems with the electrode material. Use of other systems such as aqueous KOH and liquid ammonia has been restricted because of problems occurring at the limits of the required operating temperature range. The aqueous KOH system generally will not activate at low temperatures, in addition to having storage stability problems. On the other hand, use of ammonia-based electrolytes is prevented by the high temperature vapor pressure problem.

Since the temperature requirements are so severe, and other promising electrolytes were not available, an investigation of organic electrolyte systems was undertaken. Organic electrolytes usually consist of an inorganic solute dissolved in an organic solvent of very low electrical conductivity. The conductivity of the complete electrolyte is also quite low (usually an order of magnitude or more lower than aqueous systems) which is a disadvantage in high-current-density batteries. However, this low conductivity may be useful in fast-activation reserve batteries where the initial voltage rise might otherwise be suppressed by intercell shorting through the electrolyte in the fill channel. Intercell shorting may be even further reduced by placing the solute between the electrode plates and filling the cell stack with the low conductivity solvent alone. Furthermore, organic systems are also potentially very useful in that higher voltages are possible through the utilization of the more active metals as anode materials. The use of these metals in aqueous media is restricted due to the presence of reducible hydrogen ions.

The steadily growing interest in organic electrolyte battery systems has resulted in numerous investigations (mostly government sponsored) and several general surveys. Unfortunately, none of these has been concerned with, or even readily applicable to, fuze power supplies. Because the requirements for fuze power supplies are frequently unique, this survey is an attempt to determine

Preceding page blank

which, if any, of the systems previously studied might be useful for this application. Secondarily, because this survey contains information on all systems previously investigated, it should provide a reference base for the evaluation of future proposals on organic-based systems. It should be noted here, that with few exceptions the references cited in the tables pertain to government-sponsored contract work. A list of the companies, agencies, and institutions involved, as well as a PIC (Power Information Center) sheet and contract number index are given in tables C-I, C-II, and C-III.

2. HDL REQUIREMENTS

The present approximate performance requirements of interest for batteries at HDL are threefold: (1) 10 to 1000 $\mu A/in^2$ for periods from 2 hours to 30 days, (2) 15 to 30 mA/in^2 for 180 sec with activation in less than 50 msec, and (3) 100 to 500 mA/in^2 for 180 sec with activation in 150 msec.

The primary concern of the first requirement is energy density; i.e., how long the battery can produce a given potential at a given current density. Normally, energy density figures are given in terms of watt-hours per pound (whr/lb) or energy per unit weight. Researchers at HDL, however, are usually more interested in energy per unit volume because the size of a fuze power supply is normally more critical than its weight. Therefore, data from the literature will be more useful if sufficient information is given to allow for the calculation of energy density by volume.

The second and third requirements are for short-lifetime batteries where, although energy density is of interest, power density is of primary concern. As in the case of the first requirement, researchers at HDL are more interested in volume (or area) density rather than weight density. Therefore, for any power density data to be of use it must be convertible into watts per unit volume (or area). This type of information is normally available from the literature only where polarization (current density vs. potential) data are given.

Also of importance, perhaps of primary value, to the study at HDL will be that information in the literature concerning chemical and physical behavior. For instance, the nature of fuze batteries and the specifications which govern their design make certain solvent-solute characteristics not only desirable but necessary. Therefore this type

of information can be used to determine which solvent-solute combinations would be most promising for use in a particular situation.

3. EVALUATION OF LITERATURE INFORMATION

Any working cell system must contain an electrode couple in contact with an electrolyte. These components should have certain desirable characteristics to provide optimum performance in a fuze power supply. Once these characteristics are defined, then many of the seemingly unlimited possible candidates can be eliminated on the basis of information obtained from the literature.

3.1 Electrolytes

Since it is often desirable to construct a fuze battery with the solvent in an ampule and the solute between the electrode plates, it is necessary to consider them separately, as well as combined as an electrolytic solution.

3.1.1 Solvents

Table C-IV is a complete listing of the organic solvents considered in the literature covered. Because one of the primary (and most easily defined) requirements desired for a solvent is a low freezing point, these data are included in this table. Specifications require that the solvent be a liquid down to $-65^{\circ}F$ ($-54^{\circ}C$). Therefore solvents with freezing points lower than $-65^{\circ}F$ are listed in table C-V for consideration in the study to be carried on at HDL. Additional items of data which are of interest, such as conductivities, viscosities, etc. are included in table C-V.

To prevent shorting through the fill channels found in most reserve fuze power supplies, a solvent must have low conductivity. Most organic solvents meet this requirement, in that conductivities are normally on the order of 10^{-5} ohm^{-1} cm^{-1} or lower. Resistivities (reciprocal conductivities) of this magnitude should be sufficient to prevent a lowering of voltage during activation and intercell corrosion during operation. (See appendix A for a brief discussion of the terms conductivity and resistivity.) However, it is also desirable to have a solvent which forms highly conductive solutions so that the IR drop between the electrodes will be minimized. Solution conductivity is usually optimum with solvents characterized by low viscosities and high

dielectric constants. For example, dimethyl formamide (viscosity = 0.66 centipoise and dielectric constant = 36.7 at 25°C) forms solutions an order of magnitude more conductive than methyl cyanoacetate (viscosity = 2.63 centipoise and dielectric constant = 28 at 25°C). The use of low-viscosity and/or high-dielectric-constant additives, such as ethyl ether or ethylene carbonate, has been tried with some success in improving solution conductivity.

The vapor pressure requirement for the solvent; i.e., preferably less than 100 psi at +160°F (71°C), is met by almost all of the solvents in table C-V. Generally, any solvent with a boiling point higher than 77°F (25°C) will have a vapor pressure of less than 100 psi at +160°F. In fact many of the solvents in this table have boiling points (vapor pressure = 14.7 psi) higher than +160°F.

For fast activation systems, the solvation properties of the solvent must be such that the solute (between the electrode plates) must dissolve rapidly, if not instantaneously. Generally, a polar solvent (one with a high dielectric constant) is preferable for rapid dissolution of inorganic solutes. Also, for fast activation (as well as for high conductivity, see above) the solvent should have a low viscosity.

Finally, the lowest cost per kilogram of the solvents (as found in various chemical catalogues) is listed. Certainly, low cost is of importance when high volume production is the ultimate desired end result of a study.

Study of table C-IV reveals that the dozen most widely investigated solvents are:

(1) Propylene carbonate (PC)
(2) Dimethylformamide (DMF)
(3) Butyrolactone (BL)
(4) Dimethylsulfoxide (DMSO)
(5) Acetonitrile (AN)
(6) Nitromethane (NM)
(7) Tetrahydrofuran (THF)
(8) Acetone (A)
(9) Nitrosodimethylamine (NDA)

(10) Ethyl... carbonate (EC)

(11) Methyl formate (MF)

(12) Ethyl acetate (EA)

Of the above listed solvents only DMF, THF, A, MF, EA and PC-NM mixtures have freezing points lower than -65°F and of these only MF and the PC-NM mixture have been used in a "successful" battery system. (See section 3.3 for a discussion of "successful" systems.)

3.1.2 Solutes

Table C-VI is a complete listing of the solute materials considered in the literature covered. The majority of these materials fall into five general classes of compounds: (1) simple salts; e.g., alkali and alkaline earth halides; (2) Lewis acids (electron pair acceptors); e.g., $AlCl_3$ and BF_3; (3) Lewis acids combined with alkali halides; e.g., $LiAlCl_4$ ($AlCl_3$ and LiCl); (4) complex fluorides; e.g., $NaPF_6$ and KBF_4; and (5) organically substituted ammonium salts; e.g., tetraethylammonium perchlorate. The first four classes are represented in the ten most commonly studied solutes:

(1) $LiClO_4$

(2) LiCl

(3) $AlCl_3$

(4) KPF_6

(5) $LiPF_6$

(6) $LiAlCl_4$

(7) $LiBF_4$

(8) $NaPF_6$

(9) LiF

(10) KSCN

The requirements governing the choice of solute materials are compatibility with and solubility in the solvent, low cost, and ease of handling. The first two requirements

are fairly obvious. Certainly the solute must be soluble in the solvent and it must not react with the solvent to form any solid or gaseous products. The third requirement (ease of handling) refers to the problems encountered if the solute material is gaseous, highly hygroscopic, explosive, or hazardous in any manner. The solute should be such that it can be easily handled in, at worst, dry room conditions.

3.1.3 Electrolytic Solutions

Because the available power density of a system is, in part, dependent upon the IR drop between the electrodes, the conductivity of the electrolytic solution used is of primary concern. Extensive listings of conductivities are in the literature. For specific solvent-solute combinations, mutual references in both solvent and solute tables should be checked. As mentioned earlier, solutions made with solvents possessing high dielectric constants and low viscosities have high conductivities. In general, conductivities of organic electrolytes are at least an order of magnitude lower than aqueous systems. The values found in the literature range from 5×10^{-2} to 10^{-4} ohm^{-1} cm^{-1}. For a given system, maximum conductivity is normally obtained at a concentration of about 1 molar. Above this value, a decrease in conductivity is observed, due probably to the increasing viscosity of the solution.

It has been shown that in order to develop limiting current densities of several hundred mA/cm^2, cell spacing must be on the order of 10 mils or less, and that porous electrodes must be thin, since the cell spacing involved also includes the ion path within the electrode pores.

In addition to having a high ionic conductivity, the electrolyte must also have certain other physical and chemical properties. It must not freeze above -40 F (-40 C) and must have a reasonably low vapor pressure at +140 F (+60 C). This requirement will certainly be met by all solutions made with the solvents listed in table C-V. Furthermore, the electrode materials must be essentially insoluble in, and chemically inert to, the electrolyte. However, the electrode reaction products should be soluble to prevent film formation.

The purity of the electrolyte can have a marked effect upon the performance of the cell. The presence of impurities affects not only the decomposition potential of the

solvent, but also the stability of the electrolyte by itself or with regard to the electrode materials used. The most common impurity encountered is water, either as an original constituent of the solvent, or as water of hydration with the solute or cathode materials. While the presence of water is usually detrimental, in some cases small amounts appear to be beneficial to the electrode reactions.

3.2 Electrode Couples

As with the breakdown of electrolytes into solvents and solutes, it is also desirable to consider anode and cathode materials separately and then to consider them as a couple.

3.2.1 Anode Materials

Although previously mentioned, it is worth repeating that one of the advantages of organic electrolytes is that the active alkali and alkaline earth metals can be used as anodes. (It should also be noted that some Group III metals have also received consideration as anode materials--see table C-VII.) Among the desirable characteristics exhibited by these metals are: low equivalent weights, high half-cell potentials, and large exchange currents. The high exchange currents exhibited by these materials usually yield high rates of reaction during discharge, hence lower polarization, resulting in higher possible current densities.

3.2.2 Cathode Materials

Both inorganic and organic materials have been considered for use as cathodes in organic electrolyte systems--see table C-VIII. The inorganic compounds most commonly considered are salts of the light transition metals (Cr, Mn, Fe, Co, Ni, Cu, and Zn), lead, mercury, and silver. These salts are usually the oxides (inorganic acid anhydrides), halides, sulfides, or sulfates. The organic compounds normally considered are substituted aromatics, most commonly nitrates.

Among the desirable characteristics for optimum cathode materials are a small negative free energy of formation and compatibility with the electrolyte. Also, the material should be essentially insoluble in the electrolyte, although at least a slight degree of solubility appears to be necessary for electrochemical activity to take place. Ideally, the material itself should be conductive, although PbO_2 and some nickel sulfides are the only common examples of this.

In some cases, e.g., thin electrodes for short life time applications, an electrodepositable material would be desirable to eliminate the necessity of preparing the electrode by sintering or pasting.

In the case where the cathode reaction products are an insoluble metal and a soluble salt (of the anode metal),

$$e^- + M'X \longrightarrow X^- \text{ (soluble)} + M'$$

a situation arises which can lead to improved cathode performance as discharge occurs. That is, as low density, non-conductive M'X is replaced by high density, conductive M', the electrode becomes more porous and impregnated with a conducting material.

3.2.3 Couples

The items of interest concerning an electrode couple are: the potential developed by the couple, the obtainable current density at a desired potential, and the lifetime of the couple at a desired current density.

The chemical reaction associated with any given couple can be used to determine theoretically several of these characteristics. These include the maximum possible potential which can be developed by the couple and its theoretical energy density. (See appendix B for the mathematics involved in these determinations.) In general, an electrode couple with a high cell potential is one of a cathode (positive) with a small negative free energy of formation and an anode (negative) which, together with the cathode, yields reaction products with large negative free energies of formation.

For a high energy density, the electrode materials should have high theoretical charge densities resulting from small equivalent weights.

Table C-IX shows the theoretical cell potentials for all combinations of listed anodes and cathodes yielding potentials of 2.0 volts or greater. These potentials were calculated under the assumption that the electrode couple reaction is a single replacement only:

$$M + M'X \longrightarrow M' + MX$$

Other factors; e.g., another type of reaction or solvation (complexing) of the products, may cause the couple to yield a potential higher than that calculated. This

concept is illustrated by the lead-lead dioxide system currently in use at HDL. If this were a single replacement reaction; i.e.,

$$Pb + PbO_2 \longrightarrow PbO_2 + Pb$$

the system would theoretically have zero potential. Since it does yield a useable potential, something else must be taking place; in this case, a reaction in which both reactants go to the same product, Pb^{++} ions.

Therefore, table C-IX is a guide only, and should be considered in view of the fact that couple potentials can possibly be higher than those shown. It should also be noted that, if a couple does react by means of a simple single replacement, the potential developed will be lower than the value shown due to the non-ideality of the reaction.

Available data on the current density obtainable from a given couple (with only a reasonable amount of polarization)are highly dependent upon electrode construction and electrolyte composition and purity. Generally, the organic systems which are presently considered the most successful operate in the range of 0.1 to 10 mA/cm^2 (0.65 to 65 mA/in^2).

3.3 Complete Cell Systems

Although a few companies have advanced systems to a point where they are making prototype batteries, it is generally agreed that a completely successful organic electrolyte battery has not yet been developed. In this case, a "completely successful" system denotes one that will function properly over an entire range of specifications (temperature extremes, shelf life, etc.) for the purpose for which it was designed, which might be as a rechargeable system, a high energy density, long-lifetime system, etc. however, some of these systems may still be acceptable for the unique requirements necessary for power supplies intended for use in fuzes.

Table C-X is a listing of those systems which are considered to be the most successful for their particular application. In most cases the containers and packaging for these batteries are laboratory type fixtures and are not applicable for field use.

A study of this table shows that: (1) in all cases the active anode material is lithium, although the construction

of the electrode may vary, (2) the cathode materials used are silver, nickel, or copper halides, with the exceptions CuS and ACL-70, and, (3) that the acceptable solvents (in terms of freezing point) are MF, IPA, and the combinations THF, DME and PC, NM.

The data given in this table are either taken directly from the reference cited or calculated from data given in the reference. The information listed is in most cases only part of the data in the literature, but is that which is pertinent to the study at HDL only. Any gaps in the table are the result of a lack of data in the literature.

4. DISCUSSION OF REQUIREMENTS

4.1 Long Lifetime, Low Current Drain Applications

This particular paplication presently calls for a system which will produce from 10 to 1000 $\mu A/in^2$ for periods from 2 hours to 30 days.

Tables C-XI and C-XII reflect the amounts of active anode and cathode electrode materials (in g/in^2 and thickness in mils) needed for this application. These values are calculated on the basis of a 100 $\mu A/in^2$ current drain for 30 days, assuming that the electrodes react in a single replacement type reaction. To determine the amounts needed for the specified 10 to 1000 $\mu A/in^2$ range, use N/10 to 10N where N is the quantity listed. These values then reflect the weights and thicknesses required for a 100 percent efficient discharge of non-porous materials containing no binding or conductive additives. Since cathode structures are normally porous and normally require the active material to be combined with a binder and a conductive medium, the values listed should be increased (reasonably by a factor of at least 2) to obtain a more realistic picture of the cathode material required.

The values listed for the anode materials will be reasonably accurate if the weight and thickness of any required supporting metal grid is considered.

In order to determine which cathode materials may provide optimum performance, it is necessary to determine priorities among requirements. Because the volume of the final battery is of primary concern, the material yielding the thinnest electrode at a given current density should be given first consideration. However, this approach does not

take the potential developed by the cell into account; i.e., a 2-mil thick electrode producting 2 volts is not as desirable as a 3-mil thick electrode producting 4 volts. Therefore the electrode materials should be considered in order of decreasing potential per unit thickness (volts/mil). Column 3, table C-XII is a listing of such values theoretically determined as volts (vs Li) per mil for materials producing 2.0 volts or more for which density information is available.

Also of primary concern is the solubility of the cathode material. Generally, a highly or even moderately soluble material will shorten cell life due to depletion of cathode material and chemical reaction with the anode. Information in the literature relating to the solubility of cathodes usually takes one of two forms. First, and most obvious, is that direct information on solubility in, and/or reactivity with, the electrolyte. Second is information on open-circuit, wet-stand times. The usual cause of failure in cells during open-circuit stand is dissolution of the cathode material causing chemical discharge at the anode.

In a practical sense, tests run at open circuit will be a simple method of screening potential cathode-electrolyte combinations. A cell that will not last for 30 days at +140°F at open circuit will not last for that period under a very small current drain.

4.2 Short Lifetime, Moderate Current Drain Applications

There are two applications that require systems which will operate for 180 seconds. One requires activation in less than 50 msec and operation at 15 to 30 mA/in^2. The second requires activation in 150 msec and operation at 100 to 500 mA/in^2.

The maximum amount of material required for these applications; i.e., 180 sec × 500 mA/in^2 = 90 $coulombs/in^2$, is of the same order of magnitude as the minimum requirement for the long lifetime applications; i.e., 30 days × 10 $\mu A/in^2$ = 26 $coulombs/in^2$. Therefore it is possible, although not highly probable, that the same electrodes can be used for all three applications presently being considered. When material requirements for the long lifetime applications necessitate 10 or 100 times the minimum requirement, electrode construction techniques will probably need to be modified.

One advantage to the short lifetime applications is that the cathode solubility problem is greatly reduced. Most of the systems investigated do not show signs of deterioration for at least several days. Therefore, almost all systems studied should last for 180 seconds at 140°F.

There are two major problems involved in the short lifetime applications. The first is in finding organic based systems that will activate under load in 50 msec. Since none of the previous investigations were concerned with rapid activation, there are no available data on this subject. The second will be finding systems which will maintain a reasonable potential at 500 mA/in^2. The most promising systems in the literature to date normally operate at a current drain an order of magnitude smaller than this.

5. SUMMARY AND RECOMMENDATIONS

The investigations covered by this report fall generally into one of two groups. One group is made up of those studies which are academic in nature and deal primarily with reaction mechanism and kinetics studies. The studies in this group are not directed toward the actual development of a battery system as are those studies in the second group.

The second group are those investigations (usually by a company, rather than an agency or university) which are directed primarily at the development of a marketable battery system. It is the performance data from this type of study which should be of interest to researchers at HDL. Many of the investigations of the second type were screening studies concerned primarily with the measurement of the conductivities and stabilities of electrolyte solutions and with the compatibilities and solubilities of electrode materials (primarily cathodes) in these solutions.

Of those reports which cover the testing of actual battery (or single cell) performance, approximately one half are devoted to rechargeable (secondary) systems. The data related to the charging of these systems are of little interest in one-time-only fuze power supplies. On the other hand the discharge data and the data concerning wet-stand shelf life are of general interest.

Unfortunately, it was our experience that a given set of data related to the performance of a system (either primary or secondary) would be, for our purposes, incomplete or presented in such a manner as to make an interpretation

difficult without making some assumptions. Granted that the data are usable for the purpose of the investigation in question, they are of little value in relation to work on fuze power supplies. This is because the general requirements for the systems covered; i.e., high energy density, necessitated the taking of data in ranges outside the sphere of interest to HDL. Because most responses of these systems, particularly polarization data, are not linear, extrapolation of data would be difficult if not undependable. Therefore, the data derived from these systems was useful primarily in the fact that we know qualitatively that one system works better than another.

The value of the information derived from this literature search (for researchers at HDL) is that it presents a listing of systems (table C-X) which are the best (for other applications) to date, rather than presenting specific numbers upon which we can base definite statements as to how well a system will work for our applications. This information will at least provide some guidance as to which systems will be most promising for study at HDL.

On this basis, it is presently recommended that the study at HDL begin with the determinations listed in section 5.1 on the systems listed in section 5.2.

5.1 Determinations

(1) Feasibility of rapid activation over a range of temperatures ($-40^{\circ}F$ to $+140^{\circ}F$) and loads (0 to 500 mA/in^2). This study can be done on cathode and anode materials separately.

(2) Polarization data (particularly at $-40^{\circ}F$) in the range from 0 to 500 mA/in^2.

(3) Lifetimes over a range of temperatures (particularly $+140^{\circ}F$) under very low current drains; i.e., $< 1000\ \mu A/in^2$.

(4) Effect of preparation conditions (especially with relation to inertness and dryness of the environment) upon performance of any systems found promising in 1, 2, and 3.

5.2 Systems

Anodes[a]	Solvents[b]	Solutes	Cathodes
Li	MF	$LiAlCl_4$	$CuCl_2$
Mg	PC, NM	$LiClO_4$	CuF_2
Ca	DMF	LiCl	CuS
	DMSI	$LiPF_6$	AgF_2
	PC	KPF_6	AgCl
	BL	$Mg(ClO_4)_2$	AgS
	AN	TPA BF_4	ACL-70
	ACN		

[a]Mg and Ca should be tested for comparison as well as for possible use.

[b]Some solvents listed are known to freeze above -65°F, but should be tested at least at room temperature for comparison purposes.

6. LITERATURE CITED

AIR FORCE - CAMBRIDGE RESEARCH LABS.

1. "Adsorption of Ions and Neutral Molecules at Electrode Surfaces"; Internal; Project 8659, task 865904; PIC/1199

Article; JACS, 89, 489 (1967)

2. "Ionic Conductance in Non-aqueous Solvents"; Internal; Project 8659, task 865904; PIC/1200

AMERICAN UNIVERSITY

3. "Investigation of Electrochemistry of High Energy Compounds in Organic Electrolytes"; NGR 09-003-005; NASA-LRC; PIC/1187

Quarterly report #1; Foley, Swinehart, Schubert; Apr 65; NASA CR-63741
Quarterly report #2; Foley, Schubert, Helgen; Oct 65; NASA CR-62023
Quarterly report #3; Foley, Schubert, Helgen; Apr 66; NASA CR-62034
Supplement to QR #3; Foley, Marciniszyn; Sep 66; NASA CR-78235
Quarterly report #4; Foley; Oct 66
Quarterly report #5; Foley, Bogar; Apr 67; NASA CR-85842
Final Report; Foley, Bogar; Jan 68

4. "Research on Electrochemical Energy Conversion Systems"; DA 44-009-AMC-1386(T); ARMY-MERDC; PIC/1398

Interim report; Foley, Taborek; Feb 67; AD653779
Final report; Foley; May 68
Report #5; Foley, Taborek, Bomkamp; Nov 68

ARGONNE NATIONAL LABORATORIES

5. "The Thermochemical Properties of the Oxides, Fluorides, and Chlorides"; AEC #W-31-109-ENG-38

Report #ANL-5790(1957); Glassner
Report #ANL-7650

ARMY-ELECTRONICS COMMAND (ECOM)

6. "New Electrochemical Systems"; Internal; Task DAIC014501A34A; PIC/447

"High Energy Electrochemical Battery Systems Using Organic Electrolytes" (Tech Report #ECOM 2632); Knapp; Oct 65; AD627215

"Status Report on Organic Electrolyte High Energy Density Batteries" (Report #ECOM-2844); Braeuer, Harvey; May 67; AD654813

7. "New Electrochemical Systems"; Internal; Task 1G6-22001A-053-02-26; PIC/937

8. "Electrochemical Evaluation of Porous Cathode Structures in Organic Electrolytes"; Internal; IT061102A34A-00-201-C8; PIC/1839 (see U. Calif., DAAB07-67-C-0590)

9. "Kinetic Studies of Transition Metal Cathodes in Organic Electrolytes"; Internal; IT061102A34A-00-211-C8; PIC/1840

10. "New Cathode Materials for Organic Electrolyte Batteries"; Internal. IT662705A05302-721-C8, IT622001A053-02-721-C8; PIC/1857

"Feasibility Study of the Lithium/C_xF Primary Cell" (R and D Tech. Report #ECOM 3322); Braeuer; Aug 70

11. "Electrokinetics and Mechanism Research"; Internal; DA ITO-14501 A 34A00000; PIC/1933

"Synthesis and Characterization of Intermediate Compounds Involved in the Electrochemical Reduction of m-Dinitrobenzene" (Tech Report #ECOM 3222)

12. "Nitroaromatic Reduction Mechanisms"; Internal; 61145011-IT014501A 34A00000-C8; PIC/1982 (paper presented to Electrochem. Soc., May 69)

13. "Organic Electrolyte Batteries-Conference Papers"; NASr-191; PIC-Bat 209/10

Report (4 papers; King, Marsh, Braeuer, Knight); Jan 67; AD813045

14. "Characterization of Organic Electrolyte Batteries"; Internal; IT6-62705A-053-02-723; PIC/2376

15. "Reserve Organic Electrolyte Batteries"; Internal; IG6-63702DG10-01-132; PIC/2377

16. "Organic Electrolyte Battery Cathodes (Interstitial Compounds of Graphite)"; Internal; IT061102A34A; PIC/2392

ARMY-MOBILITY EQUIPMENT RESEARCH AND DEVELOPMENT CENTER (MERDC)

17. "Electrode Reactions in Organic Electrolyte Solutions"; Internal; IT061102B13A; PIC/2203

ATOMICS INTERNATIONAL

18. "Development of a Lightweight Secondary Battery System"; DA36-039-SC-88925; ARMY-ECOM; PIC/561

Final report (AI-7823); Osteryoung, et al.; Nov 62; AD 290326

19. "Improved Cathode Systems for High-Energy Primary Batteries"; F19628-67-C-0387; AIR FORCE-CRL; PIC/1833

Report (AI-68-93); Nicholson; Dec 68; AD845244

20. "Improved Cathode Systems for High-Energy Primary Batteries"; F19628-70-C-0086; AIR FORCE-CRL; PIC/2189

BATTELLE MEMORIAL INSTITUTE

21. "Investigation of Porous Lithium Battery Electrodes"; AF 33(615)-2619; AIR FORCE-WP; PIC/1473

Quarterly report #1; McCallum, et al.; Dec 65; AD474692
Quarterly report #2, McCallum, et al.; Jan 66; AD478016
Quarterly report #3; McCallum, et al.; Apr 66; AD484218
Quarterly report #4; McCallum, et al.; Jul 66; AD487623
TECH report #AFAPL-TR-67-13; McCallum, Semones, Faust; Feb 67; AD808937

22. "Battery Information: Personalizing This Emerging Resource" (Title of one of fourteen reports produced under this contract); AF-33(615)-3701; AIR FORCE-WP; PIC/1517

TECH Report #AFAPL-TR-69-40; Johnson, McCallum, Miller; May 69

23. "Preparation of Pure Cupric Fluoride"; NA?3-10942; NASA-LRC; PIC/1895

Final report; Lundquist; Sep 69; NASA CR-72571

24. "Lithium Battery Research"; F33-615-68-C-1282; AIR FORCE-WP; PIC/2091

Tech report #AFAPL-TR-69-48; McCallum, Semones, Tidwell; Jun 69
Tech report #AFAPL-TR-70-38; Semones, Tidwell, McCallum; Jun 70
Tech report #AFAPL-TR-71-49; Semones, McCallum; Jun 71
Tech report #AFAPL-TR-71-82; Semones, McCallum; Sep 71

CARNEGIE INSTITUTE OF TECHNOLOGY

25. "Electrochemical Studies in Non-Aqueous Solvents"; NBS-R-09-022-029

Report; Gedansky, Pribadi; 1967; NASA CR-84657

CASE WESTERN RESERVE UNIVERSITY

26. "Organic Electrode Processes in Non-Aqueous Solvents"; N123(62738)-56006A; NAVY-NWC/COR; PIC/1544

Article; Srinivasan, Kuwana; J. Phys. Chem., 72, 1144 (1968)
Article; Osa, Kuwana; J. Electroanal. Chem. and Interfac. Chem., 22, 389 (1969)
Report (NWCCL TP 795); Kuwana; Oct 68; AD843141

EAGLE-PICHER INDUSTRIES, INC.

27. "Organic Electrolyte Battery for Manpack"; DAAB07-71-C-0131; ARMY-ECOM; PIC/2387

ELECTRIC STORAGE BATTERY CO. (ESB)

28. "High Energy System (Organic Electrolyte)"; DA-28-043-AMC-01394(E); ARMY-ECOM; PIC/1435

Quarterly report #1; Boden, Buhner, Spera; Oct 65; AD628961
Quarterly report #2; Boden, Buhner, Spera; Jan 66; AD630691

Quarterly report #3; Boden, Buhner, Spera; Jun 66; AD634491
Final report (Tech report #ECOM-01394-F); Boden, Buhner, Spera; Sep 66; AD639709

29. "High Energy System (Organic Electrolyte)"; DA-28-043-AMC-02304 (E); ARMY-ECOM; PIC/1435

Quarterly report #1; Boden, Buhner, Spera; Dec 66; AD643935
Quarterly report #2; Buhner, Spera; Feb 67; AD648920
Quarterly report #3; Buhner, Spera; Jun 67; AD643785
Final report (Tech report #ECOM-02304-F); Boden, Buhner, Spera; Sep 67; AD659419

30. "High Energy System (Organic Electrolyte)"; DAAB07-67-C-0385; ARMY ECOM; PIC/1435

Semi-Annual report #9 (Tech report #ECOM-0385-1); Boden, Buhner, Spera; Feb 68; AD666230
Final report #10 (Tech report #ECOM-0385-F); Boden, Buhner, Spera; Oct 68; AD676867

ELECTROCHEMICA CORP (ELCA)

31. "Research and Development of a High Energy Non-Aqueous Battery"; NOw 63-0618-C; NAVY-NOSC; PIC/1266

Final report; Eisenberg, Pavlovic; May 65

32. "Research and Development of a High Energy Non-Aqueous Battery"; NOw 65-0506-C; NAVY-NOSC; PIC/1266

Report; Eisenberg; Jul 65

33. "Research on a High Energy Non-Aqueous Battery System; "NOw 66-0342-C; NAVY-NOSC; PIC/1266

Quarterly report #1; Eisenberg; Mar 66; AD481014
Quarterly report #2; Eisenberg; Jun 66
Quarterly report #3; Eisenberg; Sep 66; AD802208
Quarterly report #4; Eisenberg; Dec 66; AD808475
Quarterly report #5; Eisenberg; Mar 67; AD813321
Quarterly report #6; Eisenberg; Jun 67; AD818935
Final report; Eisenberg, Wong; Sep 67; AD825131

34. "Research on a High Energy Non-Aqueous Battery System"; N00017-68-C-1401; NAVY-NOSC; PIC/1266

Quarterly report #1; Eisenberg; Dec 67; AD826310
Quarterly report #2; Eisenberg; Mar 68; AD832005
Quarterly report #3; Eisenberg; May 68
Quarterly report #4; Eisenberg; Sep 68
Quarterly report #5; Eisenberg; Dec 68
Quarterly report #6; Eisenberg; Mar 69
Quarterly report #7; Eisenberg; Jun 69
Final report; Eisenberg; Oct 69
Quarterly report #1; Eisenberg; Jan 70 ("Research on Electrochemical Parameters for Non-Aqueous Batteries.")
Quarterly report #2; Eisenberg; Apr 70. ("Research on Electrochemical Parameters for Non-Aqueous Batteries.")
Quarterly report #3; Eisenberg; Jul 70. ("Research on Electrochemical Parameters for Non-Aqueous Batteries.")
Final report; Eisenberg, Wong; Nov 70. ("Research on Electrochemical Parameters for Non-Aqueous Batteries.")

35. "Research and Development of a High Energy Non-Aqueous Battery Power Source"; N00017-71-C-1410; NAVY-NOSC; PIC/1266

Quarterly report #1; Eisenberg; Feb 71
Quarterly report #2; Eisenberg; May 71
Quarterly report #3; Wong; Aug 71

36. "Organic Electrolyte Batteries"; DAAB07-68-C-0240; ARMY-ECOM; PIC/1991

GLOBE-UNION INC.

37. "Development of High Energy Density Primary Batteries, 200 WHP of Total Battery Weight Minimum; NAS3-2790; NASA-LRC; PIC/896

Quarterly report #1; Towle: Oct 63; NASA CR-55055
Quarterly report #2; Towle; Jan 64; NASA CR-53111
Quarterly report #3; Towle; Apr 64; NASA CR-56449
Final report; Elliott, Hsu, Towle; Jul 64; NASA CR-54153

38. "A Program to Develop a High Energy Density Primary Battery with a Minimum of 200 WHP of Total Battery Weight";NAS3-6015; NASA-LRC; PIC/896

Quarterly report #1; Elliott, et al.; Oct 64; NASA CR-54187
Quarterly report #2; Elliott, et al.; Jan 65; NASA CR-54298
Quarterly report #3; Elliott, et al.; Apr 65; NASA CR-54375
Quarterly report #4; Elliott, et al.; Aug 65; NASA CR-54450
Quarterly report #5; Elliott, et al.; Oct 65; NASA CR-54744
Quarterly report #6; Elliott, et al.; Jan 66; NASA CR-54873
Quarterly report #7; Elliott, et al.; Apr 66; NASA CR-54928
Quarterly report #8; Elliott, et al.; Jul 66; NASA CR-72040
Quarterly report #9; Elliott, et al.; Oct 66; NASA CR-72158
Quarterly report #10; Elliott, et al.; Jan 67; NASA CR-72189
Final report; Elliott, Amlie; Sep 67; NASA CR-72364

39. "Lithium-Moist Air Battery"; DA-44-009-AMC-1552(T); ARMY-MERDC; PIC/1490

Semi-annual report #1; Toni, McDonald, Elliott; Oct 66; AD642248
Interim tech report; Mar 67
Final report; Toni, Zwaagstra; Jul 67

40. "Organic Electrolyte Battery"; 58-0690, 58-4116, 58-5214, 58-5291; Sandia Corp; PIC/1634

Final report (SC-CR-67-2855); McDonald, Murphey, Gower; Dec 67
Final report (SC-CR-69-3084); McDonald; Apr 69
Final report (SC-CR-69-3290); McDonald; Nov 69

GULTON INDUSTRIES INC.

41. "Lithium-Nickel Halide Secondary Battery Investigation"; Internal

Quarterly report #1; Lyall, Seiger, Shair; May 64; AD433616

Quarterly report #2; Lyall, Seiger, Shair; Jun 64; AD601148
Quarterly report #3; Lyall, Seiger, Shair; Sep 64; AD605754

42. "Lithium-Nickel Halide Secondary Battery Investigation"; AF33(615)-1265; AIR FORCE-WP; PIC/987

Quarterly report #1; Lyall; Mar 64; AD464485
Quarterly report #2; Lyall; Jun 64; AD468352
Quarterly report #3; Lyall, Seiger; Sep 64; AD474394
Final tech report #AFAPL-TR-65-11; Lyall, Seiger, Shair; Jan 65; AD612492
Final tech report #AFAPL-TR-65-128; Lyall, Seiger, Shair; Mar 66; AD478992

43. "Lithium-Nickel Fluoride Secondary Battery Investigation"; AF33(615)-3488; AIR FORCE-WP; PIC/1553

Quarterly report #1; Lyall; Aug 66
Quarterly report #2; Lyall, et al.; Nov 66; AD803529
Quarterly report #3; Lyall, et al.; Feb 67; AD808839
Supplement to QR #3; Lyall, et al.; Feb 67; AD816378
Quarterly report #4; Lyall, et al.; May 67
Quarterly report #5; Lyall, et al.; Apr 67
Quarterly report #6; Lyall, et al.; Nov 67; AD824659
Quarterly report #7; Lyall, et al.; Feb 68
Final report #AFAPL-TR-68-71; Lyall, Seiger, Orshich; Jul 68

44. "Non-Aqueous Electrolyte Secondary Batteries"; NIH-69-2153; NIH; PIC/2273

LIVINGSTON ELECTRONIC CORP.

45. "Development of High Energy Density Primary Batteries 200 WHP of Total Battery Weight Mimimum"; NAS3-2775; NASA-LRC; PIC/898

Quarterly report #1; Meyers; et al.; Aug 63; NASA CR-52550
Quarterly report #2; Meyers; Nov 63; NASA CR-55743

Quarterly report #3; Meyers; Feb 64; NASA CR-54024
Final report; Meyers; NASA CR-54083

46. "Development of High Energy Density Primary Batteries 200 WHP Total Battery Weight Minimum"; NAS3-6004; NASA-LRC; PIC/1201

Quarterly report #1; Abens, Meyers; Oct 64; NASA CR-54118
Quarterly report #2; Abens, Meyers; Dec 64; NASA CR-54307
Quarterly report #3; Abens, Mayers; Mar 65; NASA CR-54659
Final report; Meyers, et al.; Jun 65; NASA CR-54803

47. "Development of High Energy Density Primary Batteries"; NAS3-7632; NASA-LRC; PIC/1463

Quarterly report #1; Abens, Mahy, Merz; Dec 65; NASA CR-54859
Quarterly report #2; Abens, Mahy, Merz; Dec 65; NASA CR-54920
Quarterly report #3; Abens, Corbett, Merz; Mar 66; NASA CR-54992
Quarterly report #4; Abens, Corbett, Merz; Jun 66; NASA CR-72071
Final report; Abens, Merz, Walk; Mar 67; NASA CR-72331

48. "Development of High Energy Density Primary Batteries"; NAS3-10613; NASA-LRC; PIC/1772

Topical report; Abens; Jan 68; NASA CR-72416
Final report; Abens, Merz, Walk; Apr 68; NASA CR-72535

49. "Lithium Battery for Air-Sea-Rescue-Radios"; N00019-68-C-0614; NAVY-NASC; PIC/2178

50. "High Energy Density Primary Battery"; NAS3-13221; NASA-LRC; PIC/2312

LOCKHEED AIRCRAFT CORP

51. "New Cathode-Anode Couples using Non-Aqueous Electrolytes"; AF33(616)7957; AIR FORCE-WP; PIC/677

Tech. doc. report #ASD-TDR-62-1; Chilton; Apr 62; AD277171
Annual tech report #ASD-TDR-62-837; Chilton, Cook; Sep 62; AD285889
Quarterly tech report #1; Bauman, Chilton, Cook; Dec 62; AD294308
Quarterly tech report #2; Bauman, Chilton, Cook; Apr 63; AD401846
Quarterly tech report #3; Bauman, Chilton, Cook; Jul 63; AD417856
Tech doc. report #RTD-TDR-63-4083; Bauman, Chilton, Conner, Cook; Oct 63; AD425876

52. "Lithium-Silver Chloride Secondary Battery Investigation"; AF33(615)1195; AIR FORCE-WP; PIC/677

Quarterly report #1; Chilton, Conner, Holsinger; Apr 64; AD439399
Quarterly report #2; Chilton, Conner, Holsinger; Jul 64; AD450428
Quarterly report #3; Chilton, Holsinger; Oct 64; AD607968
Final report #AFAPL-TR-64-147; Chilton, Conner, Cook, Holsinger; Feb 65; AD612189

53. "Lithium Anode Limited Cycle Secondary Battery"; AF33(657)-11709; AIR FORCE-WP; PIC/861

Quarterly report #1; Bauman; Sep 63; AD418339
Quarterly report #2; Bauman; Dec 63; AD426791
Quarterly report #3; Bauman; Mar 64; AD433543
Tech doc report #APL-TDR-64-59, Bauman; May 64; AD601128; ("Limited Cycle Secondary Battery using Lithium Anode.")

54. "Litnium Anode Limited Cycle Battery Investigation"; AF33(615)2455; AIR FORCE-WP; PIC/1216

Quarterly report #1; Bauman, Chilton, Mauri; May 65; AD463556
Quarterly report #2; Bauman, Chilton, Mauri; Aug 65; AD468674
Quarterly report #3; Bauman, Chilton, Mauri; Nov 65; AD474219
Quarterly report #4; Bauman, Chilton, Mauri; Feb 66
Quarterly report #5; Bauman; May 66; AD483237
Quarterly report #6; Bauman, Chilton, Hultquist; Aug 66; AD489624
Quarterly report #7; Bauman, Chilton, Hultquist; Nov 66; AD804103

Tech report #AFAPL-TR-66-35; Bauman, Chilton, Mauri; Apr 66; AD481543
Tech report #AFAPL-TR-67-104; Bauman, Chilton, Hultquist; Jul 67; AD821051

MALLORY AND CO., INC.

55. "Research and Development of a High Capacity Non-Aqueous Secondary Battery"; NAS3-2780; NASA-LRC; PIC/947

Quarterly report #1; Selim, Hill
Quarterly report #2; Selim, Hill; NASA CR-53087
Quarterly report #3; Selim, Hill
Quarterly report #4; Selim, Hill; NASA CR-54164
Final report; Hill, Selim; Aug 65; NASA CR-54880

56. "Research and Development of a High Capacity Non-Aqueous Secondary Battery"; NAS3-6017; NASA-LRC; PIC/1176

Quarterly report #1; Selim, Hill; NASA CR-54319
Quarterly report #2; Selim, Hill; NASA CR-54407
Quarterly report #3; Selim, Hill, NASA CR-54732
Quarterly report #4; Selim, Hill; NASA CR-54874
Final report; Selim, Hill, Rao; Feb 66; NASA CR-54969

57. "Evaluation of Rechargeable Lithium-Copper Chloride Organic Electrolyte Battery System"; DA-44-009-AMC-1537(T); ARMY-MERDC; PIC/1489

Tech report #1; Rao, Hill; Sep 66; AD643378
Tech report #2; Rao, Hill; Mar 67; AD654451
Final report; Dey, Rao; Nov 67; AD825241

58. "Long Shelf Life Organic Electrolyte Battery"; DAAB07-70-C-0076; ARMY-ECOM; PIC/2149

MIDWEST RESEARCH INSTITUTE

59. "Preparation of Pure Lithium Hexafluorophosphate"; NAS3-12979; NASA-LRC; PIC/2146

MONSANTO RESEARCH CORP

60. "Development of the Dry Tape Battery Concept"; NAS3-2752, NAS3-4168, NAS3-9168; NASA-LRC; PIC/393

Final report; Gruber, et al.; Dec 65; NASA CR-347

61. "Dry Tape Battery Concept"; NAS3-7624; NASA-LRC; PIC/1500

Quarterly report #1: Driscoll; NASA CR-54780
Quarterly report #2; Driscoll; NASA CR-54902
Quarterly report #3; Driscoll; NASA CR-54981
Quarterly report #4; Driscoll; NASA CR-54771
Quarterly report #5; Driscoll; NASA CR-72170
Final report; Driscoll; Apr 67

62. "Research and Development of the Dry Tape Battery Concept"; NAS3-9431; NASA-LRC

Final report; Driscoll, Williams; Sep 68; NASA CR-72464

NASA-LEWIS RESEARCH CENTER

63. "Electrochemical Reactions and Materials Investigation (High Energy Batteries)"; Internal, 123-34-01-P9914; PIC/1178

"Electrolyte Solvent Properties of Organic Sulfur Derivatives"; NASA TM X-1283; Johnson; Aug 66
Solute and Cathode Investigations in Propylene Glycol Sulfite"; NASA TM X-1380; Johnson; Jun 67

64. "High Energy Couples"; Internal; 120-34-12-00-22-(K3055); PIC/2154

NAVAL ORDNANCE LABORATORY - WHITE OAK

65. "Evaluation of ELCA Experimental Non-Aqueous Electrochemical Cells (and Batteries)"; Internal: TASK-ORD-033-127-F108-06-03: TASK-ORD-333-006/UF-17-331-301

NOLTR 68-101; Conen, Norr; Jul 68
NOLTR 70-68; Rosen; Apr 70

NAVAL RESEARCH LABORATORIES

66. "An Investigation of the Possibility of using the Alkali or Alkaline Earth Metals as the Active Materials in a Battery"

NRL report #P-2503; Dirkse; Mar 45

NAVAL ORDNANCE LABORATORY-CORONA

67. "Chemoelectric Energy Conversion for Non-Aqueous Reserve Batteries"; Internal; ORD TASK-ORD-033-321/215-1/F009-06-04; Air Task-A34-340/211-1/R010-01 01 (see U. Calif-L.A.; N123(62738)57439A)

"Ionic Melt Electrochemistry-Dimethyl Sulfone" (NAVWEPS REPORT 8193); Panzer; May 64

NAVAL WEAPONS CENTER-CORONA LAB

68. "Non-Aqueous Voltaic Cell Research"; Internal; RRRE-06017/211-1/F009-06-05; PIC/1270

Quarterly report #NWCCL TP 792; Panzer; Oct 68

69. "Investigations of Beryllium Anodes in Non-Aqueous Electrolyte Solutions"; Internal; 120-34-0202; PIC/1901

Report (NWCCL TP 795); Panzer, et al.; Oct 68; AD843141
Report (NWCCL TP 822); Panzer, et al.; Jan 69: AD847137
Report; Panzer, et al.; Apr 69; NASA ER-9085
Final report; Panzer; Oct 69

70. "Radio Beacon Battery Development"; Internal; Air Task A36533/216/69F15222601; PIC/2021

Report; McWilliams

POWER CONVERSION, INC.

71. "Non-Reserve Organic Electrolyte Battery"; DAAB07-71-C-0130; ARMY-ECOM; PIC/2388

RENSSELAER POLYTECHNIC INSTITUTE

72. "Electrochemical Power Sources (Themis 840)"; DAAB07-69-C-0063; ARMY-ECOM; PIC/2246

Article, Littman; "Polarization Phenomena in Conductance Measurements in Electrolyte Solutions"; J. Electrochem. Soc.

ROCKETDYNE

73. "High Energy Battery System Study"; DA-36-039-AMC-03201 (E); ARMY-ECOM; PIC/960

Quarterly report #1; Farrar, et al.; Sep 63; AD429290
Quarterly report #2; Farrar, et al.; Dec 63; AD435627
Quarterly report #3; Farrar, et al.; Mar 64; AD452714
Quarterly report #4; Farrar, et al.; Jun 64; AD450559
Quarterly report #5; Farrar, et al.; Sep 64; AD458472
Quarterly report #6; Farrar, et al.; Dec 64; R-5405-6; AD616385
Quarterly report #7; Farrar, et al.; Mar 65; AD617714
Final report; Farrar, Keller, Nicholson; Jun 65; AD622818

74. "Properties of Non-Aqueous Electrolytes"; NAS3-8521; NASA-LRC; PIC/1649

Quarterly report #1; Keller, et al.; Sep 66; NASA CR-72106
Quarterly report #2; Keller, et al.; Dec 66; NASA CR-72168
Quarterly report #3; Keller, et al.; Mar 67; NASA CR-72065
Quarterly report #4; Keller, et al.; Jun 67; NASA CR-72277
Quarterly report #5; Keller, et al.; Sep 67; NASA CR-72324
Quarterly report #6; Keller, et al.; Mar 68; NASA CR-72407
Final report; Keller, Foster, Hanson, Hon, Muirhead; Dec 68; NASA CR-1425

75. "Investigations of Electrolyte Systems for Lithium Batteries"; NAS3-12969; NASA-LRC; PIC/2366

Final report; NASA CR-72803

SAFT

76. "System-Lithium/Ether-Lithium Perchlorate/Copper Sulfide; Internal

Paper; Gabano, Gerbier, Laurent; "Primary Cells with Non-Aqueous Electrolytes"

77. "System-Lithium/Halogenated Ester-Lithium Tetrachloroaluminate/Copper Chloride"; Internal

Paper; Gabano, Lehmann, Gerbier, Laurent; "Reversible Cells with Lithium Negative Electrodes and Copper Chloride Positive Electrodes."

SPRAGUE ELECTRIC CO.

78. "Silver Chloride/Lithium Button Cells"; Internal Article; Cook; Mar 69

79. "Solubility of Nickel Chloride and the Complex Ions Formed in Propylene Carbonate Solutions"; Internal Article; Cook; Jul 69

STANFORD RESEARCH INSTITUTE

80. "Development of High Energy Batteries"; NASw-111

Final report; Chilton, Duffek, Reed; Apr 61; NASA CR-74410

TRW, INC.

81. "NASA-Sponsored Work on Batteries and Related Electrochemistry"; NAS7-538; NASA-DC; PIC/1664

Report; NASA SP-172; Bauer

82. "Voltammetric Studies of Non-Aqueous Systems"; DA-28-043-AMC-02464(E); ARMY-ECOM; PIC/1873

Semi-Annual report #1 (Tech report #ECOM-02464-1); Paez, Seo, Silverman; Apr 67; AD655271
Final report #2 (Tech report #ECOM-02464-F); Fogle, Seo, Silverman; Dec 67; AD668936

83. "A Study to Develop a Low Temperature Battery Suitable for Space Probe Applications"; NAS3-6018

Final report; Sparke; 64; NASA CR-54737

TYCO LABORATORIES, INC.

84. "An Analysis of All Potentially Useful High Energy Battery Systems" NOw-64-0653-f; NAVY-NASC; PIC/1268

Final report; Jasinski; Jul 65; AD474950

85. "High Energy Batteries"; NOw-66-0621-C; NAVY-NASC; PIC/1268

Quarterly report #1; Jasinski; Aug 66
Quarterly report #2; Jasinski; Dec 66
Quarterly report #3; Jasinski; et al.; Mar 67
Final report; Jasinski, Burrows, Malachesky; Oct 67; AD823304

86. "Research on Electrode Structures for High Energy Density Batteries"; N00019-67-C-0680; NAVY-NASC; PIC/1268

Quarterly report #1; Jasinski, et al.; Sep 67
Quarterly report #2; Jasinski, et al.; Dec 67
Quarterly report #3; Jasinski, et al.; Mar 68
Final report; Jasinski, Malachesky, Burrows; Jul 68; AD847944

87. "High Energy Batteries"; N00019-68-C-0402; NAVY-NASC; PIC/1268

Quarterly report #1; Jasinski, et al.; Jul 68
Quarterly report #2; Jasinski, et al.; Oct 68
Final report; Jasinski, Gaines, Malachesky, Burrows; Jan 69

88. "Study of Kinetics of Alkali Metal Deposition and Dissolution in Non-Aqueous Solutions"; AF19(628)5525; AIR FORCE-CRL; PIC/1405

Final report (AFCRL-68-0560); Cogley, Butler; Oct 68; AD681453

89. "Study of the Composition of Non-Aqueous Solutions of Potential Use in High Energy Density Batteries"; AF19 (628)-6131; AIR FORCE-CRL; PIC/1689

Article; Butler, Cogley; Anal. Chem. 39, 1799 (1967); AD668747
Article; Butler, Cogley; J. Electrochem. Soc., 115, 445(1968); AD672610
Article; Butler, Cogley; J. Phys. Chem., in press
Article; Butler, Cogley; Advances in Electrochem. and Electrochem. Eng., Vol. 7, in press
Final report; Butler, Cogley, Synnott, Holleck: Sep 69; AD699589

90. "Purification and Analysis of Non-Aqueous Solvents"; F19628-68-C-0052; AIR FORCE-CRL; PIC/1832

Report #2 (AFCRL-69-0381); Jasinski; Jul 69; AD697037

91. "Study of the Composition of Non-Aqueous Solutions of Potential Use in High Energy Density Batteries"; F19628-70-C-0095; AIR FORCE-CRL; PIC/2188

UNIVERSITY OF CALIFORNIA-BERKELEY

92. "Organic Electrolyte Permselective Membranes"; DAAB07-67-C-0590; ARMY-ECOM; PIC/1872

Annual report (Tech report #ECOM-0590-F); Dampier; Sep 69

93. "Elucidation of Electrochemical Reactions and Systems"; N123(62738)33116A; NAVY-NWC/COR; PIC/346

Final report (NAVWEPS REPORT 8228); Tobias; Jan 65

UNIVERSITY OF CALIFORNIA-LOS ANGELES

94. "Non-Aqueous Electrolyte Systems"; DA-44-009-AMC-1661(T); ARMY-MERDC; PIC/1596

Interim report #1; (UCLA report #67-6); Bennion, Yao, D'Orsay; Jan 67; AD653799
Interim report #2; (UCLA report #67-52); Bennion, Yao, D'Orsay; Sep 67; AD826554
Report #3 (UCLA report #69-30); Yao, Bennion; Jun 69; AD857191
Report #4 (UCLA report #69-31); Yao, Bennion; Jun 69; AD857192
Report #5 (UCLA report #69-32); Yao, Bennion; Jun 69; AD857193

95. "Electrochemical Reduction of mDNB in DMSO"; N123(62738)-57439A; NAVY-NWC/COR; PIC/1614

NOLC report #737; Bennion, et al.; Aug 67; AD658111
NOLC report #746; Bennion, et al.; Dec 67; AD825474
NOLC report #769; Bennion, et al.; Dec 67; AD832693
Thesis; Bennion, Dunning; Jul 68; AD676318
Thesis; Bennion, Tiedemann
Report (NWCCL TP 795); Bennion, Tiedemann, Dunning; Oct 68; AD843141
Final report (Jul 66 - Oct 68); Bennion; Sep 69; AD701411

96. "Design Studies for High Rate, High Energy, Non-Aqueous Electrochemical Conversion Systems"; N00123-70-C-0188; NAVY-NWCCL; PIC/1614

Final report (UCLA-ENG-7078); Bennion, Dunning, Tiedemann; Dec 70

97. "Electrochemical Study in Cyclic Esters"; AEC #W-7405-ENG-48

Thesis (UCRL #8381); Harris; Jul 58
Thesis (UCRL #17202); Smyrl; Nov 66, "Oxidation Potentials in Dimethylsulfoxide"

UNIVERSITY OF MISSOURI

98. "Electrochemical Study for Use in Low Temperature Batteries"; DA36-039-SC-72363; ARMY-SigC

Quarterly report #1
Quarterly report #2
Quarterly report #3; Feb 57; AD135951
Final report; Arcand; Jul 57; AD143945

99. "Electrochemical Systems for Use in Low Temperature Batteries;" DA-36-039-SC-74994; ARMY-SigC

Quarterly report #1; Arcand, Tudor; Jul 58
Final report; Lagc, Karnes, Jennings, Smith; Mar 59; AD217485

WHITTAKER CORP.

100. "Electrochemical Characterization of Systems for Secondary Battery Application"; NAS3-8509; NASA-LRC; PIC/1618

Quarterly report #1; Shaw, et al., Aug 66; NASA CR-72069
Quarterly report #2; Shaw, et al.; Nov 66; NASA CR-72138
Quarterly report #3; Shaw, et al.; Feb 67; NASA CR-72181
Quarterly report #4; Shaw, et al.; Apr 67; NASA CR-72256
Quarterly report #5; Shaw, et al.; Aug 67; NASA CR-72293
Quarterly report #6; Shaw, et al.; Nov 67; NASA CR-72349
Quarterly report #7; Shaw, et al.; Feb 68; NASA CR-72377

Quarterly report #8; Shaw, et al.; May 68; NASA CR-72419
Quarterly report #9; Shaw, et al.; Aug 68; NASA CR-72482
Final report; Shaw, Paez, Ludwig; Jan 69; WRD-392

101. "Advanced Design Battery Power Source for Aircrew Survival Transceivers and Beacons"; F33657-68-C-0438; AIR FORCE-WP; PIC/1925

Interim Tech report; Chand, Smith; Oct 69; AD861947
Final report; Nov 70

APPENDIX A. CONDUCTIVITY

Because of the frequent misunderstanding of terms related to conductivity, a brief discussion of these terms is offered here.

Conductivity, as normally used, refers to specific conductance (K, ohm^{-1} cm^{-1}) and applies to a given concentration of solute. Further,

$$K = c/R \tag{A-1}$$

where c = cell constant (cm^{-1}) and R = resistance (ohms). Also,

$$K = 1/\rho \tag{A-2}$$

where ρ = resistivity or specific resistance (ohm · cm). Therefore,

$$R = \rho c = \rho l/A \tag{A-3}$$

where l and A refer to the length and cross section area of the test cell.

Molar Conductance is the conductivity of a standard concentration of solution. Specifically,

$$\text{Molar conductance} = 1000\ K/C \tag{A-4}$$

where C is the concentration in g·moles/liter.

Further, equivalent conductance (Λ),

$$\Lambda = \text{molar conductance}/N_e \tag{A-5}$$

where N_e is the valence of the electrolyte species; i.e., $N_e = 1$ for KCl and $N_e = 6$ for $Al_2(SO_4)_3$. Therefore,

$$\Lambda = 1000\ K/CN_e\ (ohm^{-1}\ cm^2) \tag{A-6}$$

Also, Λ normally varies linearly with the square root of concentration, and when so plotted and extrapolated to infinite dilution (zero concentration) yields a value Λ_0, or the limiting conductance,

$$\Lambda_0 = \Lambda\ (\text{infinite dilution}) \tag{A-7}$$

Preceding page blank

APPENDIX B. CALCULATION OF CELL POTENTIAL AND ENERGY DENSITY

Consider an electrode couple consisting of a metallic anode (M) and a salt (M'X) as the cathode, such that the reaction associated with this couple is a simple single replacement; i.e.,

$$pM + qM'X \longrightarrow rM' + sMX \qquad \text{(B-1)}$$

The thermodynamic equation for the calculation of cell potential is

$$E^{o} = -\Delta F_f/nF \qquad \text{(B-2)}$$

Where E^{o} is the theoretical cell potential, ΔF_f is the total free energy change for the reaction, n is the number of electrons transferred per mole of reaction and F is the standard Faraday constant. The total free energy change (ΔF_f) is the difference between the sum of the free energies of formation of the reactants and the similar sum for the products; i.e.,

$$\Delta F_f \text{ (reaction)} = \Sigma F_f \text{ (products)} - \Sigma F_f \text{ (reactants)} \qquad \text{(B-3)}$$

or in the case of reaction (B-1),

$$\Delta F_f = [sF_f(MX) + rF_f(M')] - [qF_f(M'X) + pF_f(M)] \qquad \text{(B-4)}$$

where the free energies of M and M' (elemental) are zero by convention.

From equation (B-2) it is obvious that a high negative value of ΔF_f (a high positive value of $-\Delta F_f$) will yield a high cell potential. Therefore a good electrode couple will be one of a cathode (M'X) with a high positive value of F_f compared to the value of F_f for the anode reaction product (MX). Because the free energies of formation for these compounds are normally negative, $F_f(M'X)$ should therefore be a small negative value, while $F_f(MX)$ should be a large negative value. In practice, values of F_f are normally found in kcal/mole. When F_f is expressed in this manner, the equation for cell potential becomes

Preceding page blank

$$E^{O} = -\Delta F_{f} / 23.06n \qquad \text{(B-5)}$$

The maximum theoretical energy density for an electrode couple can also be calculated from the associated chemical reaction. Basically, the sum of the charge densities for both electrodes is multiplied by the cell potential to yield the energy density. In the literature, charge densities and energy densities are commonly expressed in amp·hours per pound and watt·hours per pound, respectively. For ease in discussion, they will be dealt with here in terms of amp·seconds per gram (A·sec/g) and watt·seconds per gram (W·sec/g), where

$$1 \text{ amp (watt) hr/lb} = 7.93 \text{ amp (watt) sec/g} \qquad \text{(B-6)}$$

The charge density for an individual electrode is simply the number of coulombs (amp·secs) per gram of material i.e.,

$$A \cdot sec/g = 96500/EqW \qquad \text{(B-7)}$$

where EqW is the equivalent weight of the material.

The energy density for the electrode couple is then calculated by

$$W \cdot sec/g = E^{O} \Sigma (A \cdot sec/g) \qquad \text{(B-8)}$$

where E^{O} is the cell potential (either experimental or calculated from free energies of formation) and Σ (A·sec/g) is the sum of the charge densities for both the anode and the cathode.

If energy density per unit volume is desired, the charge densities for the individual electrodes must be multiplied by their respective densities (g/cm^3) before summing.

APPENDIX C. TABLES

(If no data are entered in any part of a table, it indicates that information is not available.)

Table C-I. Companies, agencies, and institutions involved in organic electrolyte research.

Air Force - Cambridge Research Laboratory (AF-CRL)
American University
Argonne National Laboratories
Army - Electronics Command (ECOM)
Army - Mobility Equipment Research and Development Center (MERDC)
Atomics International
Battelle Memorial Institute
Carnegie Institute of Technology
Case Western Reserve University
Eagle-Picher Industries, Incorporated
Electric Storage Battery Company (ESB)
Electrochemica Corporation (ELCA)
Globe-Union, Incorporated
Livingston Electronic Corporation (including Corson and Honeywell)
Lockheed Aircraft Corporation
Mallory and Company, Incorporated
Midwest Research Institute
Monsanto Research Corporation
NASA - Lewis Research Center (NASA-LRC)
Naval Ordnance Laboratory - White Oak (NOL-WO)
Naval Research Laboratories (NRL)
Naval Weapons Center - Corona (NWCCL)
Power Conversion, Incorporated
Rensselaer Polytechnic Institute
Rocketdyne
Societe Des Accumulateurs Fixes Et De Traction (SAFT)
Sprague Electric Company
Stanford Research Institute
TRW, Incorporated
Tyco Laboratories, Incorporated
University of California at Berkeley
University of California at Los Angeles
University of Missouri
Whittaker Corporation

Table C-II. PIC sheet index.

PIC sheet no.	Company, agency, or institution
0346	U. C. Berkeley
0447	ECOM
0561	Atomics International
0667	Lockheed
0861	Lockheed
0893	Monsanto
0896	Globe-Union
0898	Corson
0937	ECOM
0947	Mallory
0960	Rocketdyne
0987	Gulton
1176	Mallory
1178	NASA-LRC
1187	American U.
1199	AF - CRL
1200	AF - CRL
1201	Corson
1216	Lockheed
1266	ELCA
1268	Tyco
1270	NWCCL
1398	American U.
1405	Tyco
1435	ESB
1463	Honeywell
1473	Battelle
1489	Mallory
1490	Globe-Union
1500	Monsanto
1517	Battelle
1544	Case Western Reserve U.
1553	Gulton
1596	UCLA
1614	UCLA
1618	Whittaker
1634	Globe-Union
1649	Rocketdyne
1664	TRW
1689	Tyco
1772	Honeywell
1832	Tyco
1833	Atomics International
1839	ECOM
1840	ECOM

Table C-II. PIC sheet index - Continued

PIC sheet no.	Company, agency, or institution
1857	ECOM
1872	U. C. Berkeley
1873	TRW
1895	Battelle
1901	NAVWEPS
1925	Whittaker
1933	ECOM
1982	ECOM
1991	ELCA
2021	NWCCL
2091	Battelle
2140	HDL
2146	Midwest Research Inst.
2149	Mallory
2154	NASA-LRC
2178	Honeywell
2188	Tyco
2189	Atomics International
2203	MERDC
2246	Rensselaer
2273	Gulton
2312	Honeywell
2366	Rocketdyne
2376	ECOM
2377	ECOM
2387	Eagle-Picher
2388	Power Conversion
2392	ECOM
2439	NOL-WO

Table C-III. Index of contract numbers for organic electrolyte research.

Contract no.	Contractor
Atomic Energy Commission	
AEC W-31-109-ENG-38	Argonne National Laboratories
W-7405-ENG-48	UCLA
SC 58-0690	Globe-Union (PIC/1634)
58-4116	Globe-Union (PIC/1634)
58-5214	Globe-Union (PIC/1634)
58-5291	Globe-Union
Department of the Air Force	
AF 19(628)-5525	Tyco (PIC/1405)
19(628)-6131	Tyco (PIC/1689)
33(615)-1195	Lockheed (PIC/0677)
33(615)-1266	Gulton (PIC/0987)
33(615)-2455	Lockheed (PIC/1216)
33(615)-2619	Battelle (PIC/1473)
33(615)-3488	Gulton (PIC/1553)
33(615)-3701	Battelle (PIC/1517)
33(616)-7957	Lockheed (PIC/0677)
33(657)-11709	Lockheed (PIC/0861)
F 19628-67-C-0387	Atomics International (PIC/1833)
19628-68-C-0052	Tyco (PIC/1832)
19628-70-C-0086	Atomics International (PIC/2189)
19628-70-C-0095	Tyco (PIC/2188)
33615-68-C-1282	Battelle (PIC/2 1)
33657-68-C-0438	Whittaker (PIC/1925)
Department of the Army	
DA ABO7-67-C-0385	ESB (PIC/1435)
ABO7-67-C-0590	U. C. Berkeley (PIC/1872)
ABO7-68-C-0240	ELCA (PIC/1991)
ABO7-69-C-0063	Rensselaer (PIC/2246)
ABO7-70-C-0076	Mallory (PIC/2149)
ABO7-71-C-0130	Power Conversion (PIC/2388)
ABO7-71-C-0131	Eagle-Picher (PIC/2387)
28-043-AMC-01394(E)	ESB (PIC/1435)
28-043-AMC-02304(E)	ESB (PIC/1435)
28-043-AMC-02464(E)	TRW (PIC/1873)
36-039-AMC-03201(E)	Rocketdyne (PIC/0960)
36-039-SC-72363	U. Missouri

Table C-III. Index of contract numbers for organic electrolyte research - Continued

Contract no.	Contractor
36-039-SC-74994	U. Missouri
36-039-SC-88925	Atomics International (PIC/0561)
44-009-AMC-1386(T)	American U. (PIC/1398)
44-009-AMC-1537(T)	Mallory (PIC/1489)
44-009-AMC-1552(T)	Globe-Union (PIC/1490)
44-009-AMC-1661(T)	UCLA (PIC/1596)
Department of the Navy	
N 00017-68-C-1401	ELCA (PIC/1266)
00017-71-C-1410	ELCA (PIC/1266)
00019-67-C-0680	Tyco (PIC/1268)
00019-68-C-0402	Tyco (PIC/1268)
00019-68-C-0614	Livingston (PIC/2178)
00123-70-C-0188	UCLA (PIC/1614)
Ow-63-0618c	ELCA (PIC/1266)
Ow-64-0653f	Tyco (PIC/1268)
Ow-65-0506c	ELCA (PIC/1266)
Ow-66-0342c	ELCA (PIC/1266)
Ow-66-0621c	Tyco (PIC/1268)
123(62738)33116A	U. C. Berkeley (PIC/0346)
123(62738)56006A	Case Western Reserve University (PIC/1544)
123(62738)57439A	UCLA (PIC/1614)
National Aeronautics and Space Administration	
NAS 3-2752	Monsanto (PIC/0893)
3-2775	Livingston (PIC/0898)
3-2780	Mallory (PIC/0947)
3-2790	Globe-Union (PIC/0896)
3-4168	Monsanto (PIC/0893)
3-6004	Livingston (PIC/1201)
3-6015	Globe-Union (PIC/0896)
3-6017	Mallory (PIC/1176)
3-6018	TRW
3-7624	Monsanto (PIC/1500)
3-7632	Livingston (PIC/1463)
3-8509	Whittaker (PIC/1618)
3-8521	Rocketdyne (PIC/1649)
3-9168	Monsanto (PIC/0893)
3-9431	Monsanto
3-10613	Livingston (PIC/1772)
3-10942	Battelle (PIC/1895)

Table C-III. Index of contract numbers for organic electrolyte research - Continued

Contract no.	Contractor
3-12969	Rocketdyne (PIC/2366)
3-12979	Midwest Research (PIC/2146)
3-13221	Livingston (PIC/2312)
7-536	TRW (PIC/1664)
r-191	ECOM (PIC-BAT 209/10)
w-111	Stanford Research Institute
NBS R-09-022-029	Carnegie Tech
NGR 09-003-005	American U. (PIC/1187)
National Institute of Health	
NIH 69-2153	Gulton (PIC/2273)

Table C-IV. Solvents investigated.

No.	Solvent	Formula	Designation	MP, °C	Reference
1	Acetic acid, glacial	CH_3COOH	GAA	17	69
2	Acetic anhydride	$CH_3COOCOCH_3$	AA	-73	13
3	Acetone	CH_3COCH_3	A	-95	28,37,38,45-48,51, 94
4	Acetone diethyl sulfone	$CH_3CSO_2(C_2H_5)_2$	ADS	128	63
5	Acetonitrile (Methyl cyanide)	CH_3CN	AN	-41	1,3,6,7,13,26,28, 38-40,42,43,45,48, 51,53,56,64,68,69, 72-75,90,91,98
6	Acetylacetone	$CH_3COCH_2COCH_3$	ACA	-23	69
7	Acrylonitrile	CH_2CHCN	ACN	-82	39,40,99
8	Aldol	$CH_3CHOHCH_2CHO$	AD	--	63
9	Aluminum triethyl	$Al(C_2H_5)_3$	ATE	<-18	51
10	2-Amino-3-ethylpyridine		AEP	--	45
11	Amyl chloride	CH_3 [illegible] Cl	AC	-99	40
12	Angelicalactone	CH_3 [illegible]	AL	18	63
13	Benzene	C_6H_6	BZ	6	45,48

Table C-IV. Solvents investigated - Continued

No.	Solvent	Formula	Designation	MP, °C	Reference
14	Benzonitrile (Phenyl cyanide)	C_6H_5CN	BZN	-13	37
15	Butanedinitrile (Succinonitrile)	$CNCH_2CH_2CN$	BDN	54	29,73
16	Butane sultone	$CH_2(CH_2)_3OSO_2$	BST	--	63
17	2 Butanone	$CH_3COC_2H_5$	2B	-86	39,40
18	N-Butyl alcohol	C_4H_9OH	BAL	-90	40
19	N-Butylamine	$C_4H_9NH_2$	NA	-50	45
20	Butyl butyrate	$C_3H_7COOC_4H_9$	BB	-91	46,47
21	Butylene glycol sulfite	$O(CH_2)_4OSO$	BGS	--	94
22	1,3 Butylene sulfite	$CH_3CH(CH_2)_2SO_3$	BSI	--	94
23	[illegible] butyl ether	C_4H_9O[illegible]	BE	-98	40
24	Butyl formate	HCOO	BF	-90	46,47
25	N-Butylphthalate	$C_6H_4(COOC_4H_9)_2$	BP	--	24
26	Butyric anhydride	$C_3H_7COOCOC_3H_7$	BAH	-75	40

Table C-IV. Solvents investigated - Continued.

No.	Solvent	Formula	Designation	MP, °C	Reference
27	Butyrolactone	$CH_2(CH_2)_2COO$	BL	-44	1,3,4,6,10,13,24 31,33,40,43,45-48, 51,53,54,56,57,68, 69,84,85,87,90, 100,101
28	Butyronitrile	$CH_3(CH_2)_2CN$	BN	-113	40
29	Cacodyl oxide	$[(CH_3)_2As]_2O$	CO	-25	63
30	p-Chlorobenzotrifluoride	$C_6H_2ClF_3$	CBF	--	45
31	1-Chloro-2-propanone (Chloroacetone)	$ClCH_2COCH_3$	CA	-44	29
32	Crotononitrile	$CH_3(CH)_2CN$	CN	-84	29
33	Cyclohexanone	$CH_2(CH_2)_4CO$	CH	-45	6,24,40,45,48
34	Cyclopentanone	$CH_2(CH_2)_3CO$	CP	-58	24,94
35	Diacetone alcohol	$(CH_3)_2COHCH_2COCH_3$	DAA	-54	40
36	2,2-Dichlorodiethyl ether	$(CH_2ClCH_2)_2O$	DDE	-50	29
37	p-Dichlorotoluene (p-chlorobenzylchloride)	$CH_2ClC_6H_4Cl$	DT	29	45
38	Diethoxysulfide	$C_2H_3OSOC_2H_5$	DESD	--	63

Table C-IV. Solvents investigated - Continued.

No.	Solvent	Formula	Desig-nation	MP, °C	Reference
39	Diethyl disulfide	$C_2H_5SSC_2H_5$	DDS	--	63
40	Diethyl phosphinic acid	$(C_2H_5)_2POOH$	DPA	19	63
41	Diethyl phosphinic anhydride	$[(C_2H_5)_2PO]_2O$	DPAH	--	63
42	Diethyl sulfate	$(C_2H_5)_2SO_4$	DES	-24	63
43	Diethyl sulfite	$(C_2H_5)_2SO_3$	DESI	--	29
44	Diethyl sulfone	$(C_2H_5)_2SO_2$	DESN	73	63
45	Diethyl sulfoxide	$(C_2H_5)_2SO$	DESO	15	63
46	Diglyme (diethylene glycol dimethylether)	$(CH_3OCH_2CH_2)_2O$	DG	--	26,45,48
47	2,5 Dihydrofuran	$CHCH_2OCH_2CH$	DHF	--	29
48	Diisopropyl sulfone	$(C_3H_7)_2SO_2$	DPS	36	63
49	1,2-Dimethoxyethane	$CH_3OCH_2CH_2OCH_3$	DME	-58	24,76,77
50	N,N Dimethyl acetamide	$CH_3CON(CH_3)_2$	DMA	-20	1,24,69,94
51	Dimethyl carbonate	$(CH_3)_2CO_3$	DMC	1	6,10,29,30,43,94
52	N,N Dimethyl cyanamide	$(CH_3)_2NCN$	DMCA	-41	37,38,40

Table C-IV. Solvents investigated - Continued.

No.	Solvent	Formula	Designation	MP, °C	Reference
53	Dimethyl disulfide	CH_3SSCH_3	DMDS	-98	63
54	Dimethylformamide	$HCON(CH_3)_2$	DMF	-61	1,3,6,7,12,13,18, 26,28,37-40,42,43, 45,48,51,53,54,56, 68,69,74,75,82,84, 85,89-91,100
55	Dimethylmethane sulfonamide	$CH_3SO_2N(CH_3)_2$	DMMS	--	94
56	Dimethyl phosphorous acid	$(CH_3O)_2POH$	DMPA	--	63
57	Dimethyl sulfate	$(CH_3)_2SO_4$	DMS	-32	28,53,95
58	Dimethyl sulfite	$(CH_3)_2SO_3$	DMSI	-_10	6,69,94,95
59	Dimethyl sulfone	$(CH_3)_2SO_2$	DMSN	110	67,69,94
60	Dimethyl sulfoxide	$(CH_3)_2SO$	DMSO	19	1,2,4,6,13,18,24, 28,42,43,45,48,51, 53,54,56,67,73,75, 84,85,88-91,93-95
61	1,4 Dioxane	$CH_2O(CH_2)_2OCH_2$	1,4D	12	29,45
62	1,3 Dioxolane	$OCH_2OCH_2CH_2$	1,3D	-95	29

Table C-IV. Solvents investigated - Continued.

No.	Solvent	Formula	Desig-nation	MP, °C	Reference
63	Diphenyl ether	$(C_6H_5)_2O$	DPE	28	37,45
64	Dithioacetic acid	CH_3CSSH	DTA	--	63
65	Ethane-1,2-bis-methylthio	$CH_3S(CH_2)_2SCH_3$	EMT	--	63
66	Ethanedithiol	HSC_2H_4SH	EDT	-41	63
67	Ethane sulfonamide	$C_2H_5SO_2NH_2$	ESA	60	94
68	Ethane sulfonic acid	$C_2H_5SO_2OH$	ESNA	-17	63
69	Ethanethiol	C_2H_5SH	ETH	-144	63
70	Ethanol pyridine	$NC_5H_4C_2H_4OH$	EP	--	45
71	Ethyl acetate	$CH_3COOC_2H_5$	EA	-84	6,10,28,45-47,94
72	Ethyl acetoacetate	$CH_3COCH_2CO_2C_2H_5$	EAA	-45	46,47
73	Ethylene carbonate	$CH_2CH_2CO_3$	EC	36	1,6,10,13,30,38, 45,84,85,94
74	Ethylene diamine	$NH_2CH_2CH_2NH_2$	EDA	11	51
75	Ethylene dichloride	$ClCH_2CH_2Cl$	EDC	-40	30
76	Ethylene glycol	$HOCH_2CH_2OH$	EG	-12	42

Table C-IV. Solvents investigated - Continued.

No.	Solvent	Formula	Designation	MP, °C	Reference
77	Ethylene glycol sulfate	$O(CH_2)_2OSO_2$	EGS	99	63
78	Ethylene glycol sulfite	$O(CH_2)_2OSO$	EGSI	-11	63
79	Ethylene sulfite	$(CH_2)_2SO_3$	ENS	-11	29,94
80	Ethyl ether	$C_2H_5OC_2H_5$	EE	-116	58,59
81	Ethylethylxanthate	$C_2H_5OCS_2C_2H_5$	EEX	--	63
82	N-Ethylformamide	$HCONHC_2H_5$	EFA	--	1
83	Ethyl formate	$HCOOC_2H_5$	EF	-80	46,47
84	Ethyl isothiocyanate	C_2H_5NCS	EIT	-6	63
85	Ethyl methane sulfonate	$CH_3SO_3C_2H_5$	EMSN	-38	94
86	Ethyl sulfide	$(C_2H_5)_2S$	ESD	-103	63
87	Ethyl sulfite	$(C_2H_5)_2SO_3$	ESI	--	63,94
88	Ethyl thioacetic acid	$C_2H_5SCH_2COOH$	ETA	3	63
89	Ethyl thiocyanate	C_2H_5SCN	ETC	-86	63
90	Ethylxanthic acid	$C_2H_5OCS_2H$	EXA	-53	63

Table C-IV. Solvents investigated - Continued.

No.	Solvent	Formula	Designation	MP, °C	Reference
91	1-Fluoro-2,4-dinitrobenzene	$C_6H_3F(NO_2)_2$	FNB	26	45
92	m-Fluorotoluene	$CH_3C_6H_4F$	mFT	-111	40
93	p-Fluorotoluene	$CH_3C_6H_4F$	pFT	--	45
94	Formamide	$HCONH_2$	FM	3	6,42,45,51,84,85, 90
95	Furfuryl mercaptan (thiol)	$CH(CH)_2OCHCH_2SH$	FTH	--	63
96	Glycerol triacetate	$CH_2CHCH_2(COOCH_3)_3$	GTA	3	40
97	Glycerol tributyrate	$CH_2CHCH_2(CO_2C_3H_7)_3$	GTB	-75	40
98	Hexafluoroisopropanol	$CF_3CHOHCF_3$	HFI	--	69
99	Hexamethyl phosphoramide	$PO[N(CH_3)_2]_3$	HMPA	--	24,69,90
100	Hexyl acetate	$C_5H_{11}COOCH_3$	HA	-69	40
101	Hexylene glycol		HG	--	45
102	Hydrazine	N_2H_4	HY	2	42,64,69,84,85
103	Isoamyl alcohol	$(CH_3)_2CH(CH_2)_2OH$	AAL	-117	40

Table C-IV. Solvents investigated - Continued.

No.	Solvent	Formula	Designation	MP, °C	Reference
104	Isopropylamine	$(CH_3)_2CHNH_2$	IPA	-101	45
105	Isopropyl nitrate	$(CH_3)_2CHONO_2$	IPN	--	63
106	Lactonitrile	$CH_3CHOHCN$	LN	-40	29
107	Mesityl oxide	$(CH_3)_2CCHCOCH_3$	MSO	-59	40
108	Metnane sulfonic acid	CH_3SO_2OH	MSA	20	63
109	Methanethiol	CH_3SH	MTN	-123	63
110	Methanol	CH_3OH	M	-98	45,69
111	N-Methyl acetamide	$CH_3CONHCH_3$	MAA	28	1,51,73
112	Methyl acetate	CH_3COOCH_3	MA	-98	6,13,46,47
113	Methyl bisulfate	CH_3OSO_2OH	MS	-30	63
114	Methyl butyrate	$C_3H_7COOCH_3$	MB	<-95	40
115	Methyl chlorocarbonate	CH_3CO_2Cl	MCC	--	24,76,77
116	Methyl cyanoacetate	$CNCH_2COOCH_3$	MCA	-22	29
117	N-Methyl formamide	$HCONHCH_3$	MFA	-10	37,40
118	Methyl formate	$HCOOCH_3$	MF	-99	6,13,45-48,50,61, 62,74,75

Table C-IV. Solvents investigated - Continued.

No.	Solvent	Formula	Designation	MP, °C	Reference
119	Methyl nitrate	CH_3NO_3	MN	--	29
120	4-Methyl-2-pentanone (Isopropyl acetone)	$CH_3COCH_2CH(CH_3)_2$	MP	-85	40
121	N-methylpropionamide	$C_2H_5CONHCH_3$	MPA	--	69
122	N-Methyl-2-pyrrolidone	$CH_3N(CH_2)_3CO$	NMP	-17	42,43,45,68,69,90
123	Methyl sulfide	$(CH_3)_2S$	MSD	-83	63
124	Methyl thiocyanate	CH_3SCN	MTC	-51	40,69,92
125	Morpholine	$CH_2O(CH_2)_2NHCH_2$	MO	-5	63
126	Nitrobenzene	$C_6H_5NO_2$	NB	6	42,51
127	2-Nitro-1-butanol	$C_3H_6NO_2CH_2OH$	2NB	--	63
128	Nitroethane	$C_2H_5NO_2$	NE	-50	28
129	Nitromethane	CH_3NO_2	NM	-29	6,13,26,28,33,34, 43,45,51,53,65,75, 84,85
130	1-Nitropropane	$C_3H_7NO_2$	1NP	-108	29
131	2-Nitropropane	$CH_3CHNO_2CH_3$	2NP	-93	3,40

Table C-IV. Solvents investigated - Continued.

No.	Solvent	Formula	Designation	MP, °C	Reference
132	Nitrosodimethylamine	$(CH_3)_2NNO$	NDA	-23	4,6,13,38-40,46,49,94,95
133	2,4 Pentanedione	$CH_3COCH_2COCH_3$	2,4PD	-23	6
134	2 Pentanone	$CH_3(CH_2)_2COCH_3$	2P	-78	6,40
135	2-Picoline	$CH_3C(CH)_4N$	P	-70	3,40
136	Propane sultone	$CH_2(CH_2)_2OSO_2$	PS	--	63
137	Propanethiol	C_3H_7SH	PT	-112	63
138	Propionitrile	CH_3CH_2CN	PN	-92	28-30,40,98
139	N-Propylamine	$C_3H_7NH_2$	PA	-83	45
140	Propyl butyrate	$C_3H_7COOC_3H_7$	PB	-97	40
141	Propylbenzene (phenylpropane)	$C_6H_5C_3H_7$	PBz	-99	29,40
142	Propylene carbonate	$CH_3CHCH_2CO_3$	PC	-49	1-4,6,8-10,13,15,19-21,24,26,28-31,33,34,37-40,42,43,45-48,51-57,65,69,73-75,78,79,82,84-92,94,95,100,101

Table C-IV. Solvents investigated - Continued.

No.	Solvent	Formula	Designation	MP, °C	Reference
143	Propylene glycol sulfite	$CH_3CHOSO_2CH_2$	PGS	-70	29,63
144	Propylene sulfite	$CH_3CHCH_2SO_3$	PSI	-70	43,94
145	Pyridine	C_5H_5N	PY	-41	45,51,69
146	Tetrahydrofuran	$CH_2(CH_2)_3O$	TNF	-109	12,24,29,45-47,56, 68,69,75,76,86,87, 90
147	Tetrahydropyran	$CH_2(CH_2)_4O$	TNP	-49	24
148	Tetramethylene sulfone (Sulfolane)	$CH_2(CH_2)_3SO_2$	TMS	29	63,69,94
149	Tetramethylene sulfoxide	$CH_2(CH_2)_3SO$	TMSO	-34	94
150	Tetramethyl urea	$[(CH_3)_2N]_2CO$	TMU	--	24,29,33,37,38
151	Thiamide	NH_2CSNH_2	TAM	182	63
152	Thiazole	$CHN(CH)_2S$	TAZ	--	63
153	Thioacetone	CH_3CSCH_3	TA	--	63
154	Thioacetic acid	CH_3COSH	TAA	-17	63
155	2,2'Thiodiethanol	$HOC_2H_4SC_2H_4OH$	TE	-10	63

Table C-IV. Solvents investigated - Continued.

No.	Solvent	Formula	Desig-nation	MP, °C	Reference
156	Thioglycolic acid	$HSCH_2COOH$	TGA	-17	63
157	Thiolactic acid	$CH_3CH(SH)COOH$	TLA	10	45
158	Toluene	$C_6H_5CH_3$	T	-95	45,51
159	Triallylamine	$(CH_2CHCH_2)_3N$	TAL	--	45
160	Trichlorobenzene	$C_6H_3Cl_3$	TCB	$\geq$ 17	45
161	1,1,1-Trichloroethane	CH_3CCl_3	TCE	-33	45
162	Triethyl orthoformate	$CH(OC_2H_5)_3$	TEF	-76	40
163	Triethyl phosphine	$(C_2H_5)_3P$	TEPN	--	63
164	Triethyl phosphite	$(C_2H_5)_3PO_3$	TEP	--	29
165	Triethyl phosphoric ester	$(C_2H_5O)_3PO$	TEPE	-56	63
166	Trifluoroacetic acid	CF_3COOH	TFA	-15	69
167	Triisobutyl phosphate	$(C_4H_9O)_3PO$	TBP	--	63
168	Trimethylene disulfide	$S(CH_2)_2SCH_2$	TMD	-51	63
169	Trimethyl phosphate	$(CH_3)_3PO_4$	TMPN	--	45,48
170	Trimethyl phosphoric ester	$(CH_3O)_3PO$	TMPE	--	63

Table C-IV. Solvents investigated - Continued.

No.	Solvent	Formula	Designation	MP, °C	Reference
171	Trimethyl phosphorous ester	$(CH_3O)_3P$	TMP	--	63
172	Tripropylamine	$N(C_3H_7)_3$	TPA	<-94	40
173	Trithiane	$SCH_2SCH_2SCH_2$	TT	216	63
174	Tropone	$CH(CH)_5CO$	TP	-8	63
175	Valerolacetone	$CH_3CH(CH_2)_2COO$	VL	-31	1,3,13
176	D-Xylitol	$CH_3C_6H_4CH_2OH$	X	93	29,45

Table C-V. Solvents with freezing point below -65°F (-54°C).

No.	Designation	MP, °C	BP, °C	Viscosity (cP, 20°C)	Dielectric constant (esu, 20°C)	Density (g/ml, 20°C)	Cost ($/KG)	Comments
2	AA	-73	139	0.90		1.08	1	Highly flammable. Dehydrating agent.
3	A	-95	56	0.3	20.7	0.79	2	Highly flammable. Dissolves most plastics.
7	ACN	-82	78	0.36	37.5	0.80	2	Poisonous. Forms explosive mixtures with air (3-17%).
11	AC	-99	108	0.49	6.6	0.88	40	
17	2B	-86	80	0.35	18.5	0.81	1	Conductivity = $2 \times 10^{-6}\ \Omega^{-1}\ cm^{-1}$.
18	BAL	-90	118	2.28	17.8	0.80	2	
20	BB	-91	165			0.89	16	
23	BE	-98	142	0.58	3.1	0.76	2	Forms explosives peroxides when anhydrous.
24	BF	-90	107	0.63	6.4	0.91	40	

Table C-V. Solvents with freezing point below -65°F (-54°C) - Continued.

No.	Designation	MP, °C	BP, °C	Viscosity (cP, 20°C)	Dielectric constant (esu, 20°C)	Density (g/ml, 20°C)	Cost ($/KG)	Comments
26	BAH	-75	198	1.22	12.9	0.96	3	
28	BN	-113	118	0.52	20.3	0.79	2	Conductivity = $6 \times 10^{-6}\ \Omega^{-1}\ cm^{-1}$.
32	CN	-84	118				10	
34	CP	-58	131			0.95	14	Polymerizes in presence of acids.
35	DAA	-54	164	2.44	18.2	0.93	2	Decomposed by alkalies. Variable mp (-54 to -47).
49	DME	-54	82			0.87	6	
53	DMDS	-98	110			1.06	35	
54	DMF	-61	153	0.66	36.7	0.95	2	Conductivity = $3.8 \times 10^{-6}\ \Omega^{-1}\ cm^{-1}$.
58	DMSI	-140	126	0.77	22.5	1.21	60	Conductivity = $1.8 \times 10^{-5}\ \Omega^{-1}\ cm^{-1}$.

Table C-V. Solvents with freezing point below -65°F (-54°C) - Continued.

No.	Designation	MP, °C	BP, °C	Viscosity (cP, 20°C)	Dielectric constant (esu, 20°C)	Density (g/ml, 20°C)	Cost ($/KG)	Comments
62	1,3D	-95	78			1.06	3	
69	ETH	-144	37		6.9	0.83	10	
71	EA	-84	77	0.41	6.4	0.90	1	Slowly decomposed by moisture.
80	EE	-116	35	0.22	4.2	0.71	9	Flammable.
83	EF	-80	54	0.40	7.1	0.92	3	Decomposed by moisture.
86	ESD	-103	92		5.7	0.84	37	
89	ETC	-86	146		29.3	1.01	90	Conductivity = $1.2 \times 10^{-6}\ \Omega^{-1}\ cm^{-1}$.
92	mFT	-111	114	0.51	6.0	0.99	110	Liquid range also reported as -36° to 140°.
97	GTB	-75	315	8.10	9.0	1.03		Oily liquid.
100	HA	<-69	169	0.90	4.5	0.87	3	

Table C-V. Solvents with freezing point below -65°F (-54°C) - Continued.

No.	Designation	MP, °C	BP, °C	Viscosity (cP, 20°C)	Dielectric constant (esu, 20°C)	Density (g/ml, 20°C)	Cost ($/KG)	Comments
103	AAL	-117	130	3.25	6.2	0.81	3	"Fusel Oil." Poisonous vapors.
104	IPA	-101	33		5.5	0.69	3	Flammable.
107	MSO	-59	129	0.60	15.0	0.86	1	Oily liquid. May solidify at -40°C. Conductivity = $2.3 \times 10^{-6} \Omega^{-1}$ cm^{-1}.
109	MTH	-123	6			0.86	60	Forms crystalline hydrate. Is a gas at room temp.
110	M	-98	65	0.60	33.6	0.79	1	
112	MA	-98	57	0.41	7.2	0.93	40	
114	MB	<-95	102	0.49	5.6	0.90	80	
118	MF	-99	31	0.33	8.5	0.98	1	Poisonous vapors.
120	MP	-85	117	0.49	13.1	0.80	2	

Table C-V. Solvents with freezing point below -65°F (-54°C) - Continued.

No	Designation	MP, °C	BP, °C	Viscosity (cP, 20°C)	Dielectric constant (esu, 20°C)	Density (g/ml, 20°C)	Cost ($/KG)	Comments
123	MSD	-83	38		6.2	0.85	2	Forms addition compounds with metal halides.
130	1 NP	-108	131		23.2	1.01	3	Oily liquid.
131	2 NP	-93	118		25.5	1.02	3	
134	2P	-78	102	0.47	22.0	0.81	4	
135	P	-70	129	0.73	9.8	0.94	5	Oily liquid.
137	PT	-112	67			0.84	8	
138	PN	-?2	97	0.37	31.0	0.78	6	Extremely poisonous. Forms di- and tri-molecular compounds w/ alkalies.
139	PA	-83	48			0.72	16	
140	PB	-97	143	0.70	4.3	0.87	90	
141	PBZ	-99	159	0.70	2.3	0.86	110	

Table C-V. Solvents with freezing point below -65°F (-54°C) - Continued.

No.	Designation	MP, °C	BP, °C	Viscosity (cP, 20°C)	Dielectric constant (esu, 20°C)	Density (g/ml, 20°C)	Cost ($/KG)	Comments
143	PGS	-70	240		33.0		200	Conductivity = $5.6 \times 10^{-6} \Omega^{-1}$ cm^{-1}.
144	PSI	-70	240		33.0			
146	THF	-109	65			0.89	2	Oily liquid. Poisonous vapors. Forms explosive peroxides.
158	T	-95	110	0.60	2.4	0.87	1	
162	TEF	-76	146	0.62	6.7	0.89	7	Decomposed by presence of water.
165	TEPE	-56	215			1.07	2	Decomposed by presence of water.
172	TPA	-94	156	0.51	1.2	0.74	11	Conductivity = 8.5×10^{-9} Ω^{-1} cm^{-1}.

Table C-VI. Solute materials.

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Solute material	Literature reference
I. Inorganic	
$AlBr_3$ (43)	51
$AlCl_3$ (6)	6,13,21,24,33,34,37,42,45,46, 51-53,55,56,67,73
AlF_3 (10,·nH_2O)	24,29,37,42,45,88
$Al_2(SO_4)_3$ (5)	45
NH_4Br (5)	51
NH_4Cl (1)	42,51,88
NH_4ClO_4 (8)	88,95
$(NH_4)_2CO_3$ (1)	24
NH_4COOCH_3 (2)	88
$(NH_4)_2CrO_4$ (9)	88
$(NH_4)_2Cr_2O_7$ (3)	88
NH_4F (16)	42,88
NH_4I (28)	67
NH_4NO_3 (2)	88
NH_4PF_6 (70)	6,13,38,53,54,88
NH_4SCN (5)	6,28,51,67,88
NH_4SO_3F	37,53
$(NH_4)_2TiF_6$ (15,·$2H_2O$)	53
$SbCl_3$ (9)	37,69,88
SbF_3 (14)	37
$BaCl_2$ (3)	42,88
$Ba(ClO_4)_2$ (6)	84
$Ba(CN)_2$	24
BaF_2 (9)	42,88

Table C-VI. Solute materials - Continued.

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Solute material	Literature reference
I. Inorganic - Continued	
$Ba(NO_3)_2$ (6[a])	88
$BeCl_2$ (200)	37
BeF_2 (110)	37
BCl_3	37
BF_3 (26, 10% in CH_3OH)	29,37,74,100
$CdCl_2$ (15)	88
$Cd(CN)_2$ (70)	88
CdI_2 (29)	88
$Ca(BF_4)_2$ (122)	100
$CaCl_2$ (3,·$2H_2O$)	24,29,42,51,88,100
$CaCO_3$ (7)	29
CaF_2 (9)	24,37,40,42
$Ca(NO_3)_2$ (3,·$4H_2O$)	88
$Ca(PF_6)_2$	100
$CaSO_4$ (8)	29
$CaTiF_6$ (15)	37
$CeCl_3$ (57,·$7H_2O$)	88
$CeNH_4(NO_3)_5$ (8,$(NH_4)_2Ce(NO_3)_6$)	88
CsCl (280)	24,37,88
$CsClO_4$ (325)	84
CsF (290)	24,37,55,64
$CsPF_6$	37

[a]Explosive when anhydrous

Table C-VI. Solute materials - Continued.

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Solute material	Literature reference
I. Inorganic - Continued	
$Co(CN)_2$ (83, $\cdot 2H_2O$)	88
CoF_3 (37)	51
$CuBr_2$ (13)	51,88
$CuCl_2$ (12)	45,46,56,74,88
CuCN (10)	88
CuF_2 (450)	46,51,74,88
CuI (36)	88
$CuSO_4$ (5)	51
$HClO_4$	12,28,82
H_2O	56,82,85,91
$HONH_2 \cdot HCl$	45
H_2SO_4	13,51,84
$InBr_3$ (350)	88
$InCl_3$ (700)	37,88
$In(NO_3)_3$ (550)	88
$FeCl_3$ (4)	37,51,88
$PbCl_2$ (8)	51,88
PbF_2 (102)	42,88
$Pb(NO_3)_2$ (4)	88
$PbSO_4$ (6)	51
$LiAlCl_4$ [b]	6,8,13,33,52,54-57,75,77,78

[b] LiCl, $AlCl_3$ (usually prepared in situ).

Table C-VI. Solute materials - Continued.

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Solute material	Literature reference
I. Inorganic - Continued	
$LiAsF_6$	47,48,50,59,74,75
$LiBF_4$ (400)	6,12,13,29,42,48,53,56,69,82, 91,95,100
LiBr (19)	6,28,51,73,74,88
$LiCF_3SO_3$	95
LiCl (13)	4,13,19,21,24,28,33,34,37,38, 40,42,45,46,51-53,55-57,63, 65,67-69,74,84,88,92,94,95, 100
$LiClO_4$ (49)	3,4,6,8-10,13,15,19,20,28-30, 33,38-40,45-48,51,54,56,61, 62,68,69,74-76,82,84-88,90, 92,94,95,100,101
LiCN	24
Li_2CO_3 (10)	24,29,37,88
$LiCOOCH_3$ (19,$\cdot 2H_2O$)	88
LiF (15)	24,37,42,45,46,51,74,84,88, 91,94,100
LiI (200)	56,68,69,88
$LiNO_3$ (.1)	88,91,95
LiOH (22)	24
$LiPF_6$ (380)	13,29,37,38,42,43,47,48,51, 53,56,74,91,100
Li_2S	24
LiSCN 90)	24,73
Li_2SiF_6	37
Li_2SO_4 (14)	29,51,88
Li_2SO_3F	37
$Mg(BF_4)_2$	100
$MgBr_2$ (15,$\cdot 6H_2O$)	45

Table C-VI. Solute materials - Continued.

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Solute material	Literature reference
I. Inorganic - Contin ed	
$MgCl_2$ (6)	24,29,37,40,45,51,88,100
$Mg(ClO_4)_2$[a] (9)	6,29,45,51,84,100
$MgCO_3$ (15,basic)	29
MgF_2 (15)	24,37,42,88,100
$Mg(PF_6)_2$	100
$Mg(SCN)_2$	29
$MgSiF_6$	37
$MgSO_4$ (5)	29,45
HgBr	88
$Hg(CN)_2$ (52)	88
$Hg(COOCH_3)_2$ (30)	88
HgI_2 (30)	88
$HgSO_4$ (28)	51
$NiCl_2$ (130)	88
$Ni(CN)_2$	88
NiF_2 (320)	84,88
$Ni(PF_6)_2$	37
$NiSO_4$ (7,$\cdot 6H_2O$)	51
$NOBF_4$ (900)	53
$NOPF_6$ (840)	53
PCl_5 (4)	42
PF_5	74,100

[a]Explosive when anhydrous

Table C-VI. Solute materials - Continued.

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Solute material	Literature reference
I. Inorganic - Continued	
$KAg(CN)_2$	88
K_3AlF_6 (9)	37
$KAsF_6$ (118)	13,37,47,48
K_2BeF_4	37
KBF_4 (11)	3,13,37
KBr (3)	2,45,51,88
$KBrO_3$ (5)	51
$KCCl_3CO_2$	45
KCl (1)	24,37,42,45,51,88
$KClO_4$[a] (6)	6,47,84,88,95
KCN (8)	51,67,88
KCNO	24
K_2CO_3 (2)	24,37,88
$KCo(CN)_3$	88
$KCrF_6$	47
$K_3Cr(SCN)_6$ (67)	37
$KCu(CN)_2$	88
KF (4,·$2H_2O$)	24,37,42,45,84,88
$K_4Fe(CN)_6$ (3,·$3H_2O$)	37
$KHSO_4$ (2)	51
KI (8)	37,43,45,51,56,67,88
$KMnO_4$ (2)	51
K_2NbF_7 (174)	37
$KNi(CN)_3$	88
KNO_2 (9)	88

[a]Explosive when anhydrous

Table C-VI. Solute materials - Continued.

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Solute material	Literature reference
I. Inorganic - Continued	
KNO_3[a] (2)	51,88
KOH (670)	13,84,88
KPF_6 (30)	1-3,6,13,20,28,37,38,40,42,43, 48,51,53,68,69,84,88,100,101
K_2S	24
$KSbF_6$ (240)	48
KSCN (7)	6,24,28,45,51,67,73,84,88
K_2SiF_6 (5)	37
K_2SO_4 (1)	88
$K_2S_2O_8$ (7)	51
K_2TaF_7 (208)	37
K_2TiF_6 (9)	37
K_2ZrF_6 (12)	37
RbCl (400)	88
$RbClO_4$ (300)	84
Rb (320)	37,42,43,88
SiF_4	37
AgBr (143)	88
AgCl (69)	51,88
$AgClO_4$ (300)	56
AgI (101)	88
$AgNO_3$ (41)	45,88
Na_3AlF_6 (2)	37
$NaAsF_6$	37,47,48

[a]Explosive when anhydrous

Table C-VI. Solute materials - Continued.

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Solute material	Literature reference
I. Inorganic - Continued	
$NaBF_4$ (12)	37,40
NaBr (3)	45,88
$NaCCl_3CO_2$	45
$NaCF_3SO_3$	94
$NaCH_3SO_3$	94
NaCl (2)	13,24,37,42,45,84,88
$NaClO_4$[a] (5,·H_2O)	13,47,48,73,84,88,94
NaCN (2)	88
Na_2CO_3 (2)	24,88
$NaCOOCH_3$ (4)	88
$NaCOOC_6H_5$ (3)	88
NaF (6)	24,37,42,51,88,91
$NaHSO_4$ (5)	88
NaI (15)	43,45,88
$NaNO_2$ (2)	88
$NaNO_3$[a] (2)	51,88
$NaOCH_3$ (8)	88
NaOH (1)	88
$NaPF_6$ (192)	6,13,37,42,43,47,48,53,54,84, 88
Na_4PO_3F (21)	51
$NaSbF_6$ (90)	37,88
NaSCN (6)	88,94
Na_2SiF_6 (4)	37
Na_2SO_4 (1)	88
Na TPB[b] (750)	74,94

[a]Explosive when anhydrous

[b]See abbreviations at end of table

Table C-VI. Solute materials - Continued.

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Solute material	Literature reference
I. Inorganic - Continued	
$SrCl_2$ (4,·$6H_2O$)	88
$Sr(ClO_4)_2$ (238)	40
TlCl (25)	88,93
$SOCl_2$ (4)	42
$SnCl_2$ (8)	45
SnF_2 (43)	37
SnF_4 (3500)	37
TiF_3 (270)	37
TiF_4 (130)	37
WCl_6 (104)	88
VCl_2	88
VCl_3 (420	88
$SnCl_2$ (4)	28,88
SnF_2 (124)	42,88

Table C-VI. Solute materials - Continued.

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Solute material	Literature reference
II. Organic[b]	
(BTrMA)AsF_6	37
(BTrMA)SbF_6	37
(DBA)AsF_6	37
$(DBA)_2SiF_6$	37
(DBTrMA)PF_6	37,38
(EPy)Br (78)	51
(M)AsF_6	37
(M)PF_6	37,38,42,43,56,61,74
(nPA)BF_4	56
(PTrMA)Cl	40,42,43
(PTrMA)PF_6	37,39,40,42,43,54,88
(TAmA)SCN	94
(TBA)Br (96)	74
(TBA)F	13
(TBA)I (80)	37,84,88
(TBA)OH (153,25% CH_3OH soln)	24,40
(TBA)(TPB)	74
(TEA)Br (14)	51,88
(TEA)ClO_4 (100)	69,84-89,91
(TEA)F (620)	40,74

[b]See abbreviations at end of table

Table C-VI. Solute materials - Continued.

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Solute material	Literature reference
II. Organic[b] - Continued	
$(TMA)BF_4$ (120)	26,37,42,43,74,88
(TMA)Br (19)	37,74
(TMA)Cl (16)	3,18,37,45,51
$(TMA)ClO_4$	18
(TMA)F (600)	48,74
(TMA)I (43)	45,88
$(TMA)OH$ $(545 \cdot 5H_2O)$	40
$(TMA)PF_6$ (250)	37,38,42,43,53,74,88
$(TPA)BF_4$	37
$(TPA)ClO_4$	82
$(TPA)PF_6$ (680)	37,38
(TrABA)(TPB)	94
(TrMA)Cl (32)	45
$(TrPA)AsF_6$	37

[b]See abbreviations at end of table

Table C-VI. Solute materials - Continued.

Abbreviations

Anions	
TPB	Tetraphenylboride
Cations	
BTrMA	Benzyltrimethylammonium
DBA	Dibutylammonium
DBTrMA	Dodecylbenzyltrimethylammonium
EPy	Ethylpyridinium
M	Morpholinium
nPA	n-Propylammonium
PTrMA	Phenyltrimethylammonium
TAmA	Tetra-n-amylammonium
TBA	Tetrabutylammonium
TEA	Tetraethylammonium
TMA	Tetramethylammonium
TPA	Tetrapropylammonium
TrABA	Tri-l-amylbutylammonium
TrMA	Trimethylammonium
TrPA	Tripropylammonium

Table C-VII. Anode materials.

Material	Literature reference
1. Aluminum	13,28,33,37,39,51,52,55,73,84,94
2. Beryilium	33,37,40,51,55,69,73
3. Cadmium	33,40,100
4. Calcium	3,6,7,13,28,33,37,38,40,42,51,73,94,100
5. Cobalt	28
6. Lithium	3,4,6,8,10,12,13,15,16,18,19,21,24,27-34, 36-58,61,62,65,71.73,75-78,82-88,90,92, 94,95,100,101
7. Magnesium	3,6,7,13,28,33,37,38,40,42,45,46,51,52, 60,61,67,68,73,84,94,100
8. Potassium	3,40,51,52,94
9. Rubidium	28
10. Sodium	3,28,33,37,38,51,88,94
11. Strontium	33
12. Zinc	6,7,28,33,46,100

Table C-VIII. Cathode materials.

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Material	Literature reference
I. Elemental	
I_2	94
S	6,45,51,73
II. Inorganic	
AlF_3 (10, $\cdot nH_2O$)	45
$SbCl_5$	24
SbF_3 (14)	38,47
SbF_5	24
$AsBr_3$	24
AsF_3 (82)	24,38
AsF_5	24
B_2O_3 (4)	45
$CdCl_2$ (15)	19,24,89
$CdCO_3$	24
$Cd(CN)_2$	24
CdF_2 (60)	19,20,24,100,101
CdS (25)	24
$CrCl_2$ (300)	40,55
$CrCl_3$ (77)	29,40
CrF_2 (480)	29,40,55
CrF_3 (9, $\cdot 3\frac{1}{2} H_2O$)	28,40,51
CrI_2 (2800)	40
CrO_3 (8)	40,46,73

Table C-VIII. Cathode materials - Continued.

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Material	Literature reference
II. Inorganic - Continued	
Cr_2O_3 (4)	6,40
$Cr(OH)_2$	24
$Cr(OH)_3$	24
$CoBr_2$ (240)	40
$CoCl_2$ (111)	40,55,100
$CoCl_3$	100
$CoCO_3$ (21)	24,29
CoF_2 (80)	24,40,46,55,100
CoF_3 (37)	13,28,38,40,45-47,51,53-56,100
CoI_2 (130)	40
CoO (350)	40,100
Co_2O_3 (19)	40
Co_3O_4 (17	40
CoS	24,87
$Co(SCN)_2$	24
CuBr (55)	40
$CuBr_2$ (13)	40
CuCl (7)	19,28,30,38,40,46,56,75
$CuCl_2$ (12)	6,13,15,19,24,30-34,36,38,40, 45,56,57,65,73,74,77,92,100
$CuCO_3$ (7)	13,24,29
CuCN	24
CuCNS (60)	24
$Cu(CNS)_2$	24
CuF	19,24,28-30,40,46
CuF_2 (450)	6,13,15,19,23,24,28-34,37,38, 40,42,45-51,53,54,56,70,73-75, 84-87,94,100

Table C-VIII. Cathode materials - Continued

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Material	Literature reference
II. Inorganic - Continued	
CuI (36)	40
CuI_2	40
$Cu(IO_3)_2$ (110,·H_2O)	73
Cu_2O (3)	40
CuO (8)	13,29,40,45,46,100
Cu_2S (11)	24,38,87
CuS (8)	15,24,29,45,73,76,87
$CuSO_4$ (5)	29
AuBr	40
$AuBr_3$	40
AuCl	40
$AuCl_3$ (1680,$HAuCl_4 \cdot 3H_2O$)	40
AuI	40
Au_2O_3 (9600)	40
$GeCl_4$	24
InF_3 (1400)	100
$In(OH)_2$	24
I_2O_5 (67)	6,73
$FeBr_2$ (365)	40
$FeCl_2$ (195)	24,40,51,55
$FeCl_3$ (4)	40,55
Fe_2O_3	24,29
FeF_2 (600)	24,55
FeF_3 (500)	40,51,55,100
FeI_2 (600)	40

Table C-VIII. Cathode materials - Continued

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Material	Literature reference
II. Inorganic - Continued	
Fe_2O_3 (1)	13,29,40
Fe_3O_4	38,40
$Fe(OH)_2$	24
FeS (1)	24,87
Fe_2S_3	24,87
$PbCl_2$ (8)	51,57,89
PbF (102)	28
PbO_2 (5)	38,45,46
$Pb(OCN)_2$	24
PbS (11)	24
$PbSO_4$ (6)	51
$MnBr_2$ (140)	40
$MnCl_2$ (9)	40,55
$MnCO_3$	24
MnF_2 (270)	13,19,29,40,46,55
MnF_3 (240)	48
MnI_2 (152,·$4H_2O$)	40
MnO (12)	40
MnO_2 (7)	13,38,40,45,46,73
Mn_2O_3 (9)	40
Mn_3O_4 (9)	40
MnS	24
$HgCl_2$ (24)	51
HgO (32)	46
HgS (27)	24,51
$HgSO_4$ (28)	6,45,51

Table C-VIII. Cathode materials - Continued

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Material	Literature reference
II. Inorganic - Continued	
MoO_3 (9)	6
$NiBr_2$ (146)	40
$NiCl_2$ (130)	13,19,38,40,42,46,51,55,73,79,100
$Ni(CN)_2$	24
$NiCO_3$ (14)	24,29
NiF_2 (320)	13,19,24,28,29,37,38,40,42-46,51,73,100
NiI_2 ($120 \cdot 6H_2O$)	40
NiO (17)	38,40,100
NiO_2 (12)	40
Ni_2O_3	45
$Ni(OH)_2$	24,38
NiS	24,87
NiS_2	87
Ni_2S_3	87
$Ni(SCN)_2$	24
NO_3	38
PBr_3	24
PCl_3	24
KI (8)	94
KIO_4 (47)	60
K_2SO_4 (1)	94
$K_2S_2O_8$ (7)	73,94
Se_2Cl_2	24

Table C-VIII. Cathode materials - Continued

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Material	Literature reference
II. Inorganic - Continued	
$SiCl_4$	24
Si_2Cl_6	24
AgBr (143)	40
AgCl (69)	6,7,13,19,21,24,28,37,38,40, 46,51,52,55-57,73,78,89,94,100
AgCN (49)	24
Ag_2CO_3	24
AgF (900)	19,24,28,40,46,51
AgF_2	6,38,40,73,100
AgI (101)	40
Ag_2O (97)	13,38,40,45
AgO (330)	13,28-30,38,40,45,47,73,100
Ag_2O_3	40
Ag_7O_8	38
AgOCN (120)	24
Ag_2S	24,51,101
Ag_2SO_4 (92)	51
$NaBO_3$ (5,·$4H_2O$)	45
$NaIO_3$ (12)	73
S_2Cl_4	24
TlCl (29)	89
$SnCl_4$	24
SnO_2 (8)	45
SnS	24
TiF_3 (270)	28,29,38
TiF_4 (130)	29

Table C-VIII. Cathode materials - Continued

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Material	Literature reference
II. Inorganic - Continued	
VCl_2	40
VCl_3 (420)	40
VCl_4	24
V_2O_5 (17)	6,38,40,45,46,73
$ZnBr_2$ (25)	40
$ZnCl_2$ (4)	24,40,101
$ZnCO_3$	24
$Zn(CN)_2$	24
ZnF_2 (124)	24,40,100,101
ZnI_2 (47)	40
ZnO (1)	40
$Zn(OH)_2$	24
ZnS (6)	24,87

Table C-VIII. Cathode materials - Continued

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Material	Literature reference
III. Organic	
Bis-benzofurazane sulfone	28-30
1-Chloro-2,6-dinitrobenzene	82
N-Chlorosuccinimide	61
Dichlorobenzoquinonediimine	61
Dichloroisocyanuric acid (ACL-70)	38,46,60-62
N,N Dichloro-4-toluene-sulfonic acidamide (Dichloroamine T)	3
Dichlorotriazinetrione	6,13,60-62
2,4 Dinitroaniline	95
m-Dinitrobenzene	3,6,7,11,28-30,38,45,82,95
o-Dinitrobenzene	26
p-Dinitrobenzene	3,26,82
2,4 Dinitrophenol[a]	38,82
2,5 Dinitrophenol	82
2,6 Dinitrophenol	82
2,4 Dinitrotoluene	45
2,6 Dinitrotoluene	82
Dinitrotrichlorobenzene	3
Fluorinated graphite (C_xF)	10,16
Hexachloromelamine	38,60
2,4,6 Hexachlorotriazine-trione	60
Nitrobenzene[b]	3,12,82
4-Nitrosophenol	38
Picric acid[a]	29,60
Potassium trichloroisocyanurate	3,38,46,61
p-Quinonedixime	38
Quinone resins	18
Sodium trichloroisocyanurate	3,38,46,61
5,5'-Sulfunyl-bis-benzofurazone-3,3'-dioxide	3

[a] Explosive

[b] Liquid at room temperature

Table C-VIII. Cathode materials - Continued

(Figures in parentheses are cost, in $/kg, and available form when not anhydrous.)

Material	Literature reference
III. Organic - Continued	
Trichloroisocyanuric acid	3,38,46,61
Trichloromelamine	3,38
Trichlorotriazinetrione	61

Table C-IX. Theoretical couple potentials and free energies of formation.

Part 1. Cathodes: Free energies of formation (kcal/mole) and potentials (v) vs. various anodes.

Cathode	ΔF	Anode								
		Li	Na	K	Rb	Be	Mg	Ca	Sr	Al
SbF_3	-217	>2.9	>2.5	>2.4	>2.2	---	>2.3	>2.9	3.2	---
AsF_3	-215	3.0	2.5	2.4	2.3	---	2.3	2.9	3.2	---
$CdCl_2$	-82	2.2	2.2	2.5	2.5	---	---	2.1	2.3	---
CdF_2	-155	2.7	---	---	---	---	2.1	2.7	<2.9	---
$CrCl_2$	-85	2.1	2.1	2.4	2.4	---	---	2.1	2.2	---
$CrCl_3$	-118	2.3	2.3	2.5	2.5	---	---	2.2	2.3	---
CrF_2	-171	2.4	---	---	---	---	---	2.3	<2.6	---
CrF_3	-248	2.3	2.0	---	---	---	---	2.4	<2.7	---
CrI_2	-56	---	---	2.2	2.2	---	---	---	---	---
CrO_3	-148	---	---	---	---	---	---	2.1	---	---
$CoBr_2$	-50	2.4	2.5	2.9	2.9	---	---	2.3	<2.6	---
$CoCl_2$	-68	2.4	2.6	2.8	2.8	---	---	2.5	2.6	---
$CoCO_3$	-157	2.5	2.0	<2.5	<2.5	---	---	2.5	2.5	---
CoF_2	-147	2.9	2.4	2.4	2.2	---	2.3	2.8	<3.1	---
CoF_3	-177	3.6	3.2	3.1	2.8	2.3	3.0	3.5	<3.7	---

Table C-IX. Theoretical couple potentials and free energies of formation - Continued.

Part 1. Cathodes: Free energies of formation (kcal/mole) and potentials (v) vs. various anodes.

Cathode	ΔF	Anode								
		Li	Na	K	Rb	Be	Mg	Ca	Sr	Al
CoI_2	-23	2.3	2.0	2.8	2.8	---	---	2.3	<2.5	---
CoO	-51	---	---	---	---	2.0	---	2.0	---	---
Co_3O_4	-180	---	---	---	---	2.1	2.0	2.1	---	---
CoS	-20	2.1	---	---	---	---	---	2.1	---	---
CuBr	-24	2.5	2.6	2.9	2.9	---	---	2.4	<2.7	---
$CuBr_2$	-30	2.9	3.0	3.3	3.3	---	---	2.8	<3.1	---
CuCl	-28	2.8	2.8	3.0	3.0	---	---	2.7	2.8	---
$CuCl_2$	-42	2.9	3.1	3.3	3.3	---	2.2	3.0	3.1	---
$CuCO_3$	-124	3.2	2.7	<3.3	<3.2	---	2.6	3.2	3.2	---
CuF	-58	3.5	3.1	3.0	2.9	2.2	2.9	3.5	<3.8	---
CuF_2	-117	3.6	3.1	3.0	2.8	2.2	2.9	3.5	<3.8	---
CuI	-17	2.1	---	2.6	2.6	---	---	2.0	<2.2	---
CuI_2	-6	2.7	2.3	3.2	3.2	---	---	2.6	<2.8	---
Cu_2O	-35	2.2	---	---	---	2.3	2.2	2.4	2.1	2.0
CuO	-30	2.3	---	---	---	2.4	2.3	2.5	2.3	2.1
Cu_2S	-21	2.0	---	---	---	---	---	---	---	---
CuS	-21	2.2	---	---	---	---	---	---	---	---

Table C-IX. Theoretical couple potentials and free energies of formation - Continued.

Part 1. Cathodes: Free energies of formation (kcal/mole) and potentials (V) vs. various anodes.

Cathode	ΔF	Anode								
		Li	Na	K	Rb	Be	Mg	Ca	Sr	Al
$CuSO_4$	-158	3.2	3.1	3.4	<4.0	<2.8	2.7	3.4	3.5	---
AuBr	-4	3.4	3.5	3.8	3.8	---	2.4	3.3	<3.5	---
$AuBr_3$	-6	4.9	3.5	3.9	3.9	---	2.5	3.3	<3.6	---
AuCl	-4	3.8	3.8	4.1	4.1	2.3	2.9	3.7	3.9	2.0
$AuCl_3$	-12	3.6	3	4.1	4.1	2.3	2.9	3.7	3.9	2.0
AuI	-1	2.7	2.4	3.3	3.3	---	---	2.7	<2.9	---
Au_2O_3	+39	2.6	2.2	---	2.0	3.3	3.2	3.4	3.2	3.0
$FeBr_2$	-57	2.3	2.4	2.7	2.7	---	---	2.2	<2.5	---
$FeCl_2$	-72	2.4	2.4	2.7	2.7	---	---	2.3	2.5	---
$FeCl_3$	-80	2.6	2.8	3.1	3.1	---	---	2.7	2.9	---
$FeCO_3$	-161	2.4	---	<2.5	<2.4	---	---	2.4	2.4	---
FeF_2	-152[a]	2.8	2.3	2.2	2.1	---	2.1	2.7	<3.0	---
FeF_3	<-243[a]	>2.6	>2.1	>2.0	---	---	---	>2.5	2.8	---
FeI_2	-31	2.1	---	2.7	2.7	---	---	2.1	<2.3	---
$Fe(OH)_2$	-116	2.1	---	---	---	<2.1	---	2.1	<2.5	---

[a] Aqueous

Table C-IX. Theoretical couple potentials and free energies of formation - Continued.

Part 1. Cathodes: Free energies of formation (kcal/mole) and potentials (v) vs. various anodes.

Cathode	ΔF	Anode								
		Li	Na	K	Rb	Be	Mg	Ca	Sr	Al
FeS	-23	2.0	---	---	---	----	---	2.0	---	---
$PbCl_2$	-75	2.4	2.4	2.6	2.6	---	---	2.3	2.4	---
PbF_2	-148	2.9	2.4	2.3	2.2	---	2.2	2.8	<3.1	---
PbO_2	-52	2.4	---	---	---	2.5	2.4	2.6	2.3	2.2
PbS	-22	2.1	---	---	---	---	---	2.0	---	---
$PbSO_4$	-194	2.4	2.4	2.6	<3.2	---	---	2.6	2.7	---
$MnBr_2$	-87	---	---	2.0	2.0	---	---	---	---	---
$MnCl_2$	-106	---	---	2.0	2.0	---	---	---	---	---
MnF_2	-179	2.2	---	---	---	---	---	2.1	<2.4	---
MnF_3	<-260[a]	>2.3	---	---	---	---	---	>2.3	2.5	---
MnI_2	-60	--	--	2.1	2.1	---	---	---	---	---
$HgCl_2$	-42	3.1	3.1	3.3	3.3	---	2.2	3.0	3.1	---
[illegible]	-14	2.6	---	---	---	2.7	2.6	2.8	2.6	2.4
[illegible]	-11	2.3	---	---	---	---	---	2.2	<2.1	---
[illegible]$_4$	<-168	>3.0	>2.9	>3.2	3.8	2.6	>2.5	>3.2	>3.3	---

[a] [illegible]

Table C-IX. Theoretical couple potentials and free energies of formation - Continued.

Part 1. Cathodes: Free energies of formation (kcal/mole) and potentials (v) vs. various anodes.

Cathode	ΔF	Anode								
		Li	Na	K	Rb	Be	Mg	Ca	Sr	Al
MoO_3	-162	---	---	---	---	---	---	2.0	---	---
$NiBr_2$	-51	2.4	2.5	2.8	2.8	---	---	2.3	<2.6	---
$NiCl_2$	-65	2.6	2.6	2.8	2.8	---	---	2.5	2.6	---
$NiCO_3$	-147	2.7	2.2	<2.8	<2.7	---	2.1	2.7	2.7	---
NiF_2	-150	2.6	2.4	2.3	2.1	---	2.2	2.8	<3.0	--
NiI_2	-22	2.3	2.0	2.9	2.9	---	---	2.3	<2.5	---
NiO	-52	---	---	---	---	---	---	2.0	---	---
NiO_2	-48	2 ,	---	---	---	2.5	2.4	2.6	2.4	2.2
$Ni(OH)_2$	-108	2.3	<2.1	<2.1	---	<2.3	2.0	2.3	<2.6	---
NiS	<-18	>2.1	---	---	---	---	---	>2.1	2.0	---
AgBr	-22	2.5	2.6	2.9	2.9	---	---	2.4	<2.8	---
AgCl	-26	2.8	2.8	3.1	3.1	---	---	2.8	2.9	---
AgCN	+39	--	<2.7	<2.9	---	---	<3.0	<2.7	---	---
AgF [b]	-44	4.2	3.7	3.6	3.5	2.8	3.5	4.1	<4.4	2.3
AgF_2 [b]	-41	5.2	4.7	4.6	4.5	3.8	4.6	5.1	<5.4	3.4

		Zn	Cd	Co
[b] AgF_2	-41	2.6	2.5	2.6

Table C-IX. Theoretical couple potentials and free energies of formation - Continued.

Part 1. Cathodes: Free energies of formation (kcal/mole) and potentials (v) vs. various anodes.

Cathode	ΔF	Anode								
		Li	Na	K	Rb	Be	Mg	Ca	Sr	Al
AgI	-16	2.1	---	2.7	2.7	---	---	2.1	<2.3	---
Ag_2O	-3	2.9	---	---	---	3.0	2.9	3.1	2.8	2.7
AgO	+1	3.0	2.0	---	---	3.1	3.0	3.2	2.9	[illegible]
Ag_2O_3	+21	3.1	2.1	---	---	3.2	3.1	3.3	3.1	2.9
Ag_2S	-9	2.3	---	---	---	---	---	2.3	<2.1	---
Ag_2SO_4	-147	3.5	3.4	3.6	<4.3	<3.0	2.9	2.6	3.7	2.2
TlCl	-44	2.1	2.1	2.3	2.3	---	---	2.0	2.1	---
SnS	-20	2.1	---	---	---	---	---	2.0	---	---
TiF_4	-370	2.1	---	---	---	---	---	---	---	---
VCl_2	-97	---	---	2.1	2.1	---	---	---	2.0	---
VCl_3	-120	2.3	2.3	2.5	2.5	---	---	2.2	2.3	---
$ZnBr_2$	-74	---	2.0	2.3	2.3	---	---	---	<2.1	---
$ZnCl_2$	-88	2.1	2.1	2.3	2.3	---	---	2.0	2.1	---
ZnF_2	-163	2.5	2.1	2.0	---	---	---	2.5	<2.8	---
ZnI_2	-50	---	---	2.3	2.3	---	---	---	---	---

Table C-IX. Theoretical couple potentials and free energies of formation - Continued.

Part 2. Anode reaction products: Free energies of formation (kcal/mole).

Anode	$O^{=}$	$S^{=}$	F^{-}	Cl^{-}	Br^{-}	I^{-}	$CO_3^{=}$	$SO_4^{=}$	OH^{-}	CN^{-}
Li	-135	-115	-140	-92	-81	-64	-271	-306	-106	---
Na	-90	<-89	-129	-92	-83	-57	-250	-303	<-102	<-21
K	-76	<-100	-127	-98	-91	-77	-274	-315	<-102	<-27
Rb	<-79	<-83	-124	-98	-90	-78	<-270	<-341	<-99	---
Be	-139	<-56	-217	-112	-85	-51	---	<-286	<-216	---
Mg	-136	<-83	-251	-142	-119	-86	-246	-281	-199	<-60
Ca	-144	-114	-278	-179	-157	-127	-270	-315	-214	<-44
Sr	-134	<-108	<-290	-187	<-171	<-136	-272	-319	<-229	---
Zn	-76	-47	-163	-88	-74	-50	-175	-208	<-153	<+18
Cd	-54	-34	-155	-82	-70	-48	-160	-196	-112	<+39
Co	-51	-20	-147	-68	-50	-23	-157	-182	-109	---
Al	-377	-118	-294	-152	-121	-75	---	-739	---	---

Table C-X. Successful cell systems.

Part 1. List of cell systems.

	Cell system	Literature reference
1.	$Li/PC-LiAlCl_4/AgCl$	51,52
2.	$Li/PC-NaPF_6/CuF_2$	53
3.	$Li/PC-KPF_6/NiX_2$	42
4.	$Li/PC-LiClO_4/CuF_2$	28,46.47
5.	$Li/PC.NM-LiAlCl_4/CuCl_2$	33,34,65
6.	$Li/BL-LiClO_4/CuCl_2$	45
7.	$Li/BL-KPF_6/AgF_2$	100
8.	$Li/MF-LiClO_4/CuF_2$	46,47
9.	$Li/MF-LiClO_4$/ACL-70	61,62
10.	$Li/IPA-LiClO_4/CuS$	85
11.	$Li/THF,DME-LiClO_4/CuS$	76
12.	$Li/MCC-LiAlCl_4/CuCl$	77

Table C-X. Successful cell systems - Continued.

Part 2. Available data for cell systems listed in part 1.

Data	Literature reference

1. $Li/PC-LiAlCl_4/AgCl$ — Lockheed (51,52)

Electrolyte: 0.6M $LiAlCl_4$ in PC

Anode: Li pressed on expanded Ni
Cathode: 75% AgCl, 10% Ag, 15% inert conductor on expanded Ag.

a. Open circuit potential = 2.80 to 2.85V.

b. Time to 2.0V cut-off at given current density (mA/in^2).

CD (mA/in^2)	Time (hr)	$mA \cdot hr/in^2$
6.3	7.8	49.2
11.0	3.9	42.9
18.7	2.0	37.4
28.4	0.75	21.3
38.7	0.26	10.1

c. Current density at 2.0V at given temperature.

Temp. (^oF)	CD (mA/in^2)
-22	5.2
+28	33
+66	>65
+149	>65

2. $Li/PC-NaPF_6/CuF_2$ — Lockheed (53)

Electrolyte: $NaPF_6$ in PC (concentration unknown, likely ~1M)
Anode: Li on expanded Ag
Cathode: 70% CuF_2, 30% Ag on expanded Ag

a. Best performance: 72% utilization of CuF_2 at 1 mA/in^2 to 2.0V cut-off = 128 Whr/lb of electrode.

b. At 1 mA/in^2, obtained 200 hr of discharge to 2.0V cut-off = 200 $mA \cdot hr/in^2$.

Table C-X. Successful cell systems - Continued.

Part 2. Available data for cell systems listed in part 1.

Data	Literature reference

3. $Li/PC-KPF_6/NiX_2$ — Gulton (42)

Electrolyte: KPF_6 in PC (concentration unknown)

Anode: 90% Li, 10% graphite
Cathode: 50% NiX_2, 50% graphite

a. NiX_2 prepared by treating NiF_2 with $SOCl_2$.

b. At 2 mA/in^2, obtain 66% cathode efficiency from 3.0 to 1.0V.

c. At 100 mA/in^2, obtain 33% cathode efficiency from 1.6 to 0.6V.

4. $Li/PC-LiClO_4/CuF_2$ — Livingston (46,47); ESB (28)

Electrolyte: Livingston, 1.4M $LiClO_4$ in PC
ESB, 1M $LiClO_4$ in PC

Anode: Livingston, Li on Ag
ESB, Li on Cu

Cathode: Livingston, 83% CuF_2, 12% graphite, 6% pulp on Ag
ESB, 85% CuF_2, 10% graphite, 5% binder on Cu.

a. Open circuit potential: Livingston = 3.45V
ESB = 3.3V

b. Livingston: At 12.9 mA/in^2, obtain 15.5 hr of discharge to 2.0V cut-off.

Note: Completely self-discharged after a few days at 35°C; stable for 6 weeks at -15°C.

c. ESB: At 0.08 to 0.46 mA/in^2, obtain a voltage plateau at ~3.0V.

Note: Energy density is a maximum at ~0.3 mA/in^2 due to loss of active material through dissolution at lower drain rates. (Applies to Livingston system as well.)

Table C-X. Successful cell systems - Continued

Part 2. Available data for cell systems listed in part 1.

	Data	Literature reference
5.	Li/PC,NM-$LiAlCl_4$,$AlCl_3$/$CuCl_2$	ELCA (33,34,65)

Electrolyte: 3.0F $AlCl_3$, 0.3F LiCl in 45% PC, 55% NM
Anode: Li on Ni or Al
Cathode: 85% $CuCl_2$, 7.5% Ag, 7.5% carbon on Cu

a. Open circuit potential = 3.1V.

b. Voltage range for given current density.

CD (mA/in^2)	Voltage range
46.5	2.3 - 1.6
125	2.2 - 1.9
250	2.0 - 1.5

c. System will self-discharge due to solubility of $CuCl_2$.

6. Li/BL-$LiClO_4$/$CuCl_2$ — Livingston (45)

Electrolyte: 12% $LiClO_4$ in BL
Anode: Li
Cathode: 75% $CuCl_2$, 25% carbon

a. Open circuit potential ≅ 3.5V. (This value is higher than that theoretically calculated: 2.9V.)

b. At 6.45 mA/in^2, obtain 28 hr of discharge to 2.8V cut-off.

Note: at 3.2 mA/in^2, obtain 30 hr of discharge to 3.0V cut-off with CuF_2; OCP = 3.2V.

Table C-X. Successful cell systems - Continued

Part 2. Available data for cell systems listed in part 1.

Data	Literature reference

7. $Li/BL\text{-}KPF_6/AgF_2$ — Whittaker (100)

Electrolyte: Saturated KPF_6 in BL
Anode: Li on Ag
Cathode: AgF_2, carbon, polyethylene on Ag

a. Open circuit potential = 3.7V.

b. At 6.45 mA/in^2, obtain voltage plateau of 3.4 to 3.0V.

8. $Li/MF\text{-}LiClO_4/CuF_2$ — Livingston (46,47)

Electrolyte: 4.68F $LiClO_4$ in MF
Anode: Li on Ag.
Cathode: 83% CuF_2, 12% carbon, 6% paper on Ag

a. Open circuit potential $\cong$ 3.5V.

b. Hours of discharge at given current density to 2.0V cut-off (-15°C).

Hours	CD (mA/in^2)
1.05	129
1.25	64.5
3.4	53.5
6.2	19.4

Note: Li anode material reacts with solvent giving poor wet shelf life.

9. $Li/MF\text{-}LiClO_4$/ACL-70 — Monsanto (61,62)

Electrolyte: 1.0 F $LiClO_4$ in MF
Anode: Li
Cathode: 81% ACL-70 (dichloroisocyanuric acid), 13% Shawingan Black, 6% carbon

a. Open circuit potential = 4.0V.

b. At 50 mA/in^2, obtain 2.6 hr of discharge from 3.7 to 2.0V.
Note: "Dry Tape" system

Table C-X. Successful cell systems - Continued.

Part 2. Available data for cell systems listed in part 1.

Data	Literature reference

10. $Li/IPA-LiClO_4/CuS$ (85)

    a. For 7 amp · hr battery at 0.05 mA/in^2, obtain 95 Whr/lb with a 40% voltage drop. At 0.05 mA/in^2, obtain 190 hr of discharge to 1.5V cut-off (voltage never above 2.0V).

    b. For 2 amp · hr cell: lifetime (hr) for given CD (mA/in^2).

CD (mA/in^2)	Time (hr)
0.05	257
0.09	125
0.17	58

    c. See Y. Dechenaux, G. Gerbier, J. Laurent; Revue Bimestriella Entropie; 13; 15 (1967) for original reference.

11. $Li/THF,DME-LiClO_4/CuS$ SAFT (76)

    Electrolyte: 1M $LiClO_4$ in THF,DME
    Anode: Li
    Cathode: CuS

    a. Open circuit potential >1.95V at 20°C.

12. $Li/MCC-LiAlCl_4/CuCl$ SAFT (77)

    Electrolyte: 1M $LiAlCl_4$ in MCC
    Anode: Li on Ag
    Cathode: CuCl on Ni-plated steel

    a. Open circuit potential = 2.75V.

    Note: electrolyte decomposes above 50°C.

Table C-XI. Anode material requirements (100 μA/in^2 for 30 days).

Material	g/in^2	Mils	Material	g/in^2	Mils
Li	0.019	2.1	Ca	0.054	2.1
Na	0.062	3.9	Sr	0.118	2.8
K	0.106	7.5	Zn	0.088	0.8
Rb	0.231	9.2	Cd	0.152	1.1
Be	0.012	0.4	Al	0.024	0.6
Mg	0.033	1.2	Co	0.080	0.6

Table C-XII. Cathode (inorganic) material requirements (100 μA/in^2 for 30 days).

Material	g/in^2	Mils	V/mil[a]	Material	g/in^2	Mils	V/mil[a]
AlF_3	0.075	1.5	---	$CuBr_2$	0.301	---	---
SbF_3	0.161	2.2	1.3	CuCl	0.267	4.7	0.6
AsF_3	0.119	2.7	1.1	$CuCl_2$	0.181	3.6	0.8
B_2O_3	0.031	1.1	---	$CuCO_3$	0.166	2.5	1.3
$CdCl_2$	0.247	3.8	0.6	CuF	0.223	---	---
CdF_2	0.203	1.9	1.4	CuF_2	0.138	2.9	1.2
$CrCl_2$	0.166	3.7	0.6	CuI	0.514	5.6	0.4
$CrCl_3$	0.143	3.2	0.7	$Cu(IO_3)_2$	0.558	6.6	---
CrF_2	0.122	1.8	1.3	Cu_2O	0.193	2.0	1.1
CrF_3	0.099	1.6	1.4	CuO	0.108	1.0	2.3
CrI_2	0.413	4.9	---	Cu_2S	0.215	2.3	0.9
CrO_3	0.045	1.0	---	CuS	0.130	1.7	1.3
Cr_2O_3	0.069	0.8	---	$CuSO_4$	0.216	3.7	0.9
$CoBr_2$	0.296	3.7	0.6	AuBr	0.748	5.8	0.6
$CoCl_2$	0.176	3.2	0.7	$AuBr_3$	0.393	---	---
$CoCl_3$	0.149	3.1	---	AuCl	0.628	5.2	0.7
$CoCO_3$	0.161	2.4	1.0	$AuCl_3$	0.273	4.3	0.8
CoF_2	0.131	1.8	1.6	AuI	0.875	6.4	0.4
CoF_3	0.100	1.6	2.2	Au_2O_3	0.200	---	---
CoI_2	0.423	4.5	0.5	InF_3	0.154	2.2	---
CoO	0.101	1.0	---	I_2O_5	0.090	1.2	---
Co_2O_3	0.074	0.9	---	$FeBr_2$	0.292	3.9	0.6
Co_3O_4	0.081	0.8	---	$FeCl_2$	0.171	3.5	0.7
CoS	0.123	1.4	1.5	$FeCl_3$	0.146	3.2	0.8
CuBr	0.387	5.0	0.5	$FeCO_3$	0.157	2.5	1.0

[a]V vs Li.

Table C-XII. [illegible] (inorganic) material requirements (100 uA/in^2 for 30 days) - Continued.

Material	g/in^2	Mils	V/mil[a]	Material	g/in^2	Mils	V/mil[a]
FeF_2	0.127	1.9	1.5	$HgSO_4$	0.101	3.8	0.8
FeF_3	0.101	1.9	1.4	MoO_3	0.065	0.9	---
FeI_2	0.419	4.8	0.4	$NiBr_2$	0.296	3.9	0.6
Fe_2O_3	0.072	0.8	---	$NiCl_2$	0.276	3.0	0.9
Fe_3O_4	0.078	0.9	---	$NiCO_3$	0.161	---	---
$Fe(OH)_2$	0.121	2.2	1.0	NiF_2	0.131	1.7	1.5
FeS	0.119	1.5	1.3	NiI_2	0.423	4.5	0.5
Fe_2S_3	0.107	1.5	---	NiO	0.101	0.8	---
$PbCl_2$	0.375	3.9	0.6	Ni_2O_3	0.223	2.8	---
PbF_2	0.331	2.5	1.2	$Ni(OH)_2$	0.126	1.9	1.2
PbO_2	0.162	1.1	2.2	NiS_2	0.123	1.4	1.5
PbS	0.322	2.6	0.8	Ni_3S_2	0.162	1.7	---
$PbSO_4$	0.409	4.0	0.6	KI	0.448	8.8	---
$MnBr_2$	0.290	4.0	---	KIO_4	0.621	10.5	---
$MnCl_2$	0.170	3.5	---	K_2SO_4	0.235	5.3	---
MnF_2	0.126	1.9	1.2	$K_2S_2O_8$	0.365	8.9	---
MnF_3	0.101	1.8	1.3	AgBr	0.508	4.8	0.5
MnI_2	0.417	5.1	---	AgCl	0.386	4.2	0.7
MnO	0.096	1.1	---	AgCN	0.181	2.8	---
MnO_2	0.059	0.7	---	AgF	0.343	3.6	1.2
Mn_2O_3	0.072	1.0	---	AgF_2	0.197	2.6	2.0
Mn_3O_4	0.077	1.0	---	AgI	0.635	6.8	0.3
$HgCl_2$	0.366	4.1	0.8	Ag_2O	0.313	2.7	1.1
HgO	0.293	1.6	1.6	AgO	0.167	1.4	2.1
HgS	0.315	2.4	1.0	Ag_2S	0.335	2.8	0.8

[a]V vs Li.

Table C-XII. Cathode (inorganic) material requirements (100 μA/in^2 for 30 days)- Continued

Material	g/in^2	Mils	V/mil[a]	Material	g/in^2	Mils	V/mil[a]
Ag_2SO_4	0.421	4.7	0.7	V_2O_5	0.049	0.9	---
$NaBO_3$	0.221	---	---	$ZnBr_2$	0.304	4.4	---
$NaIO_3$	0.535	7.6	---	$ZnCl_2$	0.184	3.9	0.5
TlCl	0.648	---	---	ZnF_2	0.139	1.8	1.4
SnO_2	0.103	0.9	---	ZnI_2	0.451	5.6	---
SnS	0.204	2.4	0.9	ZnO	0.109	1.2	---
TiF_3	0.095	---	---	ZnS	0.131	2.0	---
TiF_4	0.084	1.8	1.2				
VCl_2	0.165	3.2	---				
VCl_3	0.140	2.9	0.8				

[a] V vs Li.